Quasielastic knockout of alpha clusters from light and medium nuclei by 600 MeV protons*

G. Landaud and A. Devaux
Laboratoire de Physique Nucléaire, Université de Clermont-Ferrand II, 63170 Aubière, France

P. Delpierre, J. Kahane, and R. Sené,
Laboratoire de Physique Corpusculaire, Collège de France, Paris, France

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

R. Anne
Saturne Department, Centre d'Etudes Nucléaires de Saclay, 91-Gif-sur-Yvette, France

(Received 8 June 1977; revised manuscript received 14 March 1978)

Knockout of α clusters from light and medium weight nuclei by 600 MeV protons has been investigated. The outgoing protons and α particles were detected in coincidence; their momenta were measured with two large magnetic spectrometers with proportional wire chambers. Experimental methods which were used to work with a high beam rate and an efficient proton rejection in the α arm are described. Separation energy spectra are given for ^{6}Li, ^{7}Li, ^{12}C, ^{24}Mg, ^{27}Al, and ^{40}Ca nuclei. A peak is observed at an excitation energy equal to zero, except for the ^{27}Al target.

[NUCLEAR REACTIONS ^{6}Li, ^{7}Li, ^{12}C, ^{24}Mg, ^{27}Al, ^{40}Ca$(p,p\alpha)$, E_0= 600 MeV; experimental methods; separation energy spectra.]

I. INTRODUCTION

Many experiments have been performed to provide precise information concerning clustering effects in nuclei. The study of α clusters or quartets[1] has been achieved with transfer reactions[2] but also with cluster knockout reactions. At low energy, such quasifree $(p,p\alpha)$ experiments are often dominated by sequential processes, and therefore, the target nuclei have been mainly limited to the $1p$ shell nuclei.[3-5] Increasing the incident proton energy, the α clusters can be knocked out with a reasonable cross section and a kinetic energy far higher that of an α particle issuing from sequential processes. Therefore, the quasifree $(p,p\alpha)$ reactions are favored and the detection of the α particle from inner shells can be expected. The knockout data at medium energy ($\simeq$100 MeV) must be analyzed by the distorted-wave impulse approximation (DWIA).[6] Recent progress in these calculations gives good agreement with experiment.[7,8] For energies as high as 600 MeV, distortion effects are minimized and the choice of theoretical treatment is less critical.

Our $(p,p\alpha)$ experiment was performed with a 600 MeV proton beam from the synchrotron Saturne at Saclay. Fast α particles were detected with energy between 50 and 120 MeV. The kinematic of the reaction remains close to that of free p-α scattering, although the α momentum in the nucleus could reach values of 1 fm^{-1}. Then two magnetic spectrometers of 2.5×10^{-2} sr are sufficient to detect the main part of the $(p,p\alpha)$ reactions when the energy of detected α particles is between 50 and 100 MeV. The low $(p,p\alpha)$ cross section required a beam of 10^9 protons per burst. The flux of particles in each spectrometer required the use of proportional wire chambers with low memory time. To avoid the large background due to $(p,2p)$ or (p,pd) reactions, a drastic selection on the alpha arm (ionization and range counters) was achieved.[9,10]

High energy (which imposes precise localization), large solid angles, high beam rate, and efficient proton rejection were difficult constraints. We will describe the experimental methods in some detail in Sec. II. Data analysis and separation energy spectra are discussed in Sec. III.

II. DESIGN OF THE EXPERIMENT

A. Kinematics

The quantities of interest in a $(p,p\alpha)$ experiment are the separation energy E_s of the knockout α

particle and the momentum p_R of the recoil nucleus. The separation energy can be calculated from the equation:

$$E_S = E_0 - E_1 - E_2 - E_R, \quad (1)$$

where E_0, E_1, and E_2 are the kinetic energies of the incoming proton, the knockout α particle, and the scattered proton, respectively.

The recoil nucleus energy E_R can be neglected ($E_R = p_R^2/2M_R$). E_s is related to the excitation E_X of residual nucleus by $E_s = E_X - Q$. The recoil momentum p_R can be calculated from the relation:

$$p_R = p_0 - p_1 - p_2 . \quad (2)$$

If the impulse approximation is valid, the α particle momentum q in the nucleus before the reaction is related to p_R by $q = -p_R$. To obtain the quantities E_s and p_R, it is sufficient to determine the momentum vector of the outgoing particles. The schematic diagram of our experiment is shown in Fig. 1.

B. Experimental arrangement and background limitation

The 600 MeV proton beam, extracted by a resonance method, was focused to a spot of about 1 $\times 1.5$ cm at the target position. The duty cycle was about 10% and the energy resolution was estimated as better than 1 MeV. Two double scintillation counter telescopes checked the beam position and intensity, one directed towards the target and the second towards a thin aluminum foil on the beam line far away from the target.

The scattered protons were detected after the bending magnet by four telescopes SCP (Fig. 1). To limit the γ-ray background, each of these was defined by a double scintillation counter. In these conditions, the ratio of single counting rates with and without a 20 mg/cm^2 target was about 2. All the wires of the PC2 chamber were used as a fast counter and included in the trigger. This geometrical configuration selected mainly particles coming from the target. On the α particle arm, the same background limitation was obtained with the wire chamber PC5. Besides, the large difference between the ionization of single and double charge particles gave reliable high voltage working conditions where the α particles were detected with a total efficiency and about 80% of the protons were rejected.

The α particles were detected by three telescopes after passing the bending magnet. On each one, a threshold on the thin scintillation counter SC1 (0.25 mm thickness) rejected protons. The ratio between the pulse height of the fastest α particle and the slowest proton was better than 3. The thick counter SC2 (8 mm thickness) stopped α particles up to 120 MeV. The third counter SC3 rejected particles of range greater than that of a 120 MeV α particle.

The trigger of a $(p, p\alpha)$ reaction was defined by the coincidence between counts in the proton and α arms. The target faced the α spectrometer and was limited to a 20 mg/cm^2 thickness. With an incident beam of 10^9 protons per burst on a lithium target, two coincidences were typically obtained with 10% random coincidence rate and the efficiency of the whole apparatus was equal to 0.7 ± 0.1.

C. Magnetic spectrometers and wire chambers

The direction of each outgoing particle was defined by two wire proportional chambers. Its mo-

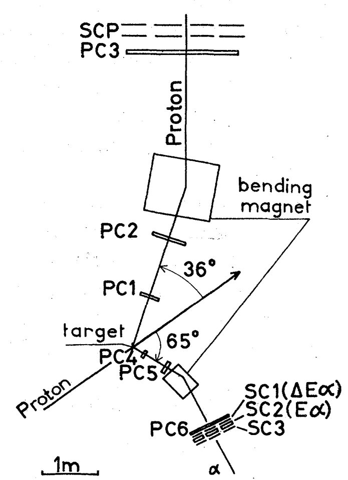

FIG. 1. Schematic diagram of the experimental setup; PC: proportional wire chamber, SCP: proton telescope, SC: scintillation counter for pulse-height analysis.

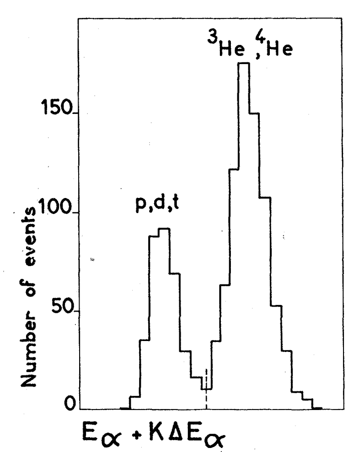

FIG. 2. Charge identification using pulse-height dependence between total and partial losses in plastic scintillator SC1 and SC2.

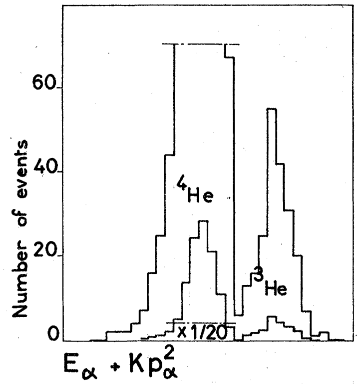

FIG. 3. ^{3}He and ^{4}He separation by the pulse height in the thick scintillator SC2 versus the momentum measured in the α-magnetic spectrometer.

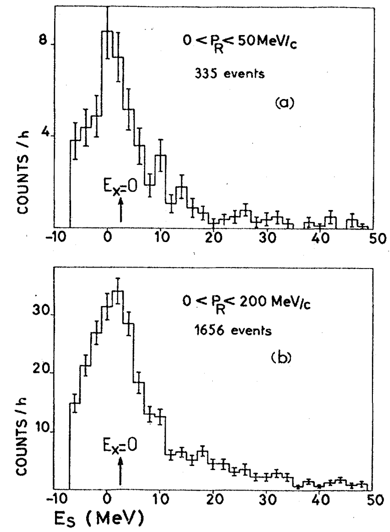

FIG. 5. The peak corresponding to the quasifree scattering is observed in the ^{7}Li$(p,p\alpha)^3$H reaction at 2.5 MeV for the binding energy.

mentum was analyzed using a bending magnet followed by a third chamber. Three wire planes per chamber gave a horizontal accuracy $\sigma_x = 0.5$ mm. Two of these planes with wires inclined at $\pm 15°$ gave the vertical coordinate with an accuracy $\sigma_y \simeq 2$ mm. In order to minimize multiple scattering of protons and α-particle absorption, the two spectrometers were equipped with helium bags.

The multiwire proportional chambers and their electronics were derived mainly from prototypes proposed by Charpak.[11] However, to avoid energy spread on the α-particle arm, the chambers were equipped with thin aluminized Mylar foil (6 μm thickness) as high voltage planes.

To reduce the electronics required by the large number of wires (~4 500), the largest chambers were encoded by a matrix procedure. Eight groups of 8 adjacent wires were connected in two different ways. A set of 8 bits defined the wires with the same position within the groups, and a second set defined the groups themselves. Thus 16 bits represented a matrix of 64 wires and the number of electronic components was divided by 4.

Fired wires, time-of-flight between proton and α (TOF) and pulse heights (ΔE_α, E_α) in SC1 and SC2 counters were recorded on magnetic tape. The data handling was checked on line with a display

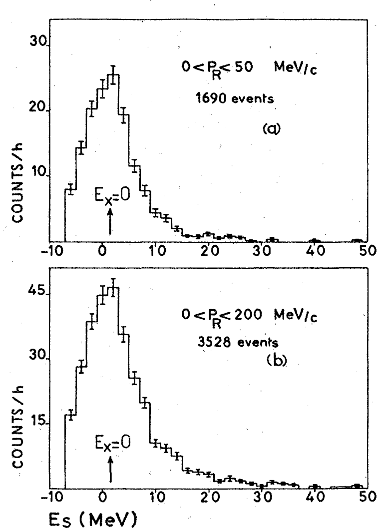

FIG. 4. Separation energy spectra for ^{6}Li with $60 < E_\alpha < 80$ MeV. The ^{6}Li $(p,p\alpha)^2$H reaction was used to measure the energy resolution (FWHM = 9 MeV).

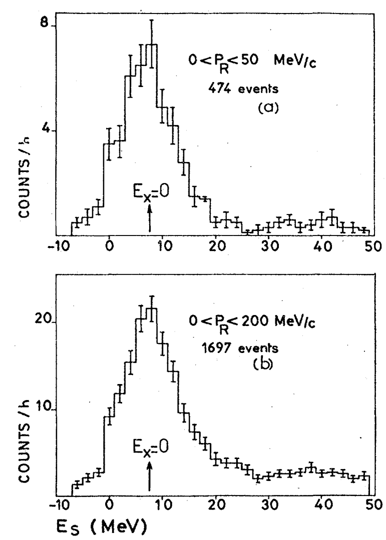

FIG. 6. For a binding energy of 7.4 MeV, the separation energy spectra in the ^{12}C$(p,p\alpha)^8$Be reaction produces a peak corresponding to the ground state of the residual nucleus. The first excited state at 2.9 MeV is not observed.

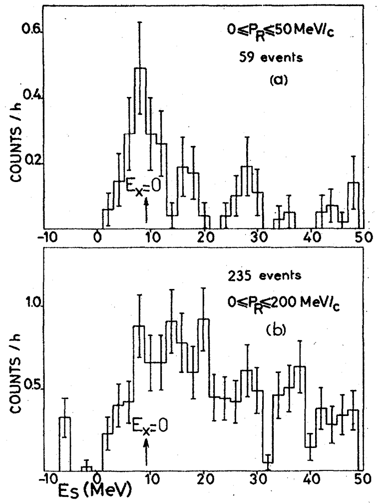

FIG. 7. The peak at 10 MeV corresponding to the quasifree scattering in the $^{24}Mg(p,p\alpha)^{20}Ne$ reaction is observed with a (0–50 MeV/c) selection in recoil momentum. In this case, and for the heavier nuclei studied, the α-energy range is extended ($50 < E_\alpha < 90$ MeV).

of the ΔE_α, E_α, TOF correlated information.

To obtain sufficient accuracy in the proton momentum calculation, a map of the magnetic field to 5 G precision had been made. Using the three components of the field,[12] a set of theoretical trajectories was precisely calculated. For data analysis, each experimental momentum was estimated by linear interpolations between the theoretical set values. The accuracy of the method was $\Delta p = 1.2$ MeV/c (FWHM) and calculation time on CDC 6 600 was about 1.5 ms. On the α-particle arm, a rough precision $\Delta p/p = 1\%$ was sufficient and gave the spread $\Delta E_\alpha = 1.5$ MeV.

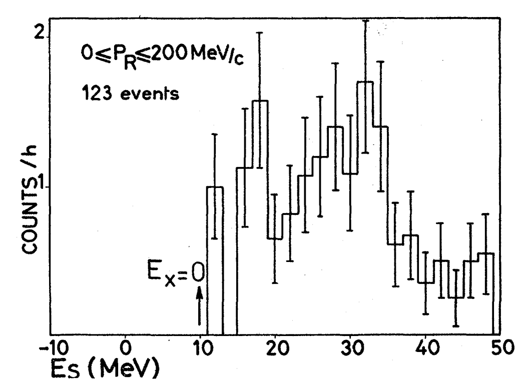

FIG. 8. No peak has been detected in the $^{27}Al(p,p\alpha)$-^{23}Na reaction, pointing out that this odd nucleus is poorly populated with α clusters.

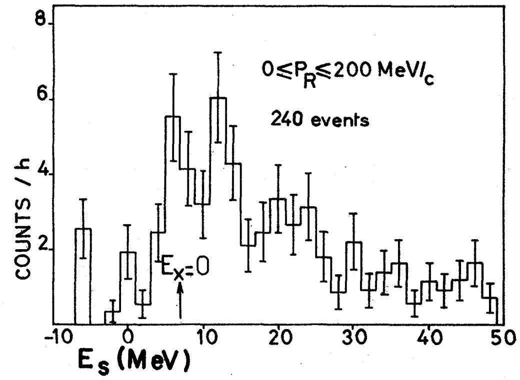

FIG. 9. The quasielastic peak, leaving the residual nucleus of the $^{40}Ca(p,p\alpha)^{36}Ar$ reaction in its ground state, appears at the binding energy of 7 MeV.

III. DATA ANALYSIS AND EXPERIMENTAL SPECTRA

We chose the following selection rules for data analysis.

(a) The intersection coordinates of the proton and α trajectories must lie within the target. This reduces random coincidences and $(p,p\alpha)$ reactions where one of the outgoing particles has been scattered by the wires.

(b) On the α arm, the correlation of E_α and ΔE_α pulse heights is connected to the charge of the particle (Fig. 2). Single-charged particles are rejected. Furthermore, if some of such unwanted particles are considered as double charge, the error on their calculated momenta will be larger than 400 MeV/c.

(c) To separate ^3He and ^4He, the calculated mo-

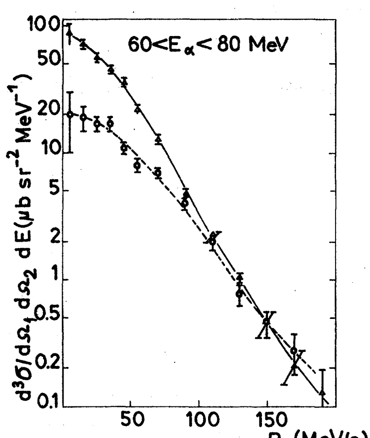

FIG. 10. The differential cross sections for ^6Li(△) and ^{12}C(○) are plotted versus the recoil momentum. Both these distributions characterize the α momentum in the nucleus before the reaction and are typical of s states.

mentum p_α is compared to the alpha energy estimated from pulse-height measurements in E_α counters (Fig. 3). A complementary selection is obtained with the time-of-flight (TOF) and the momentum.

Using Eqs. (1) and (2), the separation energy E_s and the recoil momentum p_R are calculated. To estimate the systematic error due mainly to uncertainty in the incident energy (about 5 MeV), the ^{6}Li($p,p\alpha$)^{2}H reaction is used to calibrate the separation energy scale absolutely. The peak must correspond to the value $E_s = 1.5$ MeV (Fig. 4). The experimental width of the peak is 9 MeV (FWHM) and represents an upper limit of the energy resolution.

Figures 4 to 9 show the separation energy spectra for ^{6}Li, ^{7}Li, ^{12}C, ^{24}Mg, ^{27}Al, and ^{40}Ca. To ^{24}Mg, the peak corresponding to quasifree reactions leaving the residual nucleus in its ground state is well observed, and it is enhanced by the selection of small recoil momenta [Figs. 4–7 (a)]. For ^{27}Al this peak disappears and only inelastic events corresponding to high excitation energies are detected. In the case of ^{40}Ca the peak for $E_x = 0$ is again observable.

The preliminary values of the differential cross section $d^3\sigma/d\Omega_1 d\Omega_2 dE$ for the ^{6}Li and the ^{12}C are shown in Fig. 10. For the ^{12}C the energy resolution is not sufficient to show evidence of the 2.9 MeV excited state of ^{8}Be. However, a difference in form between the ground and first excited state momentum distribution may be supposed[5] and the differential cross section (Fig. 10) shows a maximum at $P_R = 0$. That seems to indicate a low population of the first excited state.

IV. CONCLUSION

The separation energy spectra obtained with the different nuclei point out that at this energy of the incident beam (600 MeV), we have avoided the secondary reactions, and the quasielastic process dominates the reaction mechanism. Except for the ^{27}Al nucleus, we have observed a peak corresponding to quasifree reactions leaving the residual nucleus in its ground state. But we have not seen other peaks of quasielastic scattering for higher excitation energies in the range of 0–50 MeV. At this energy, the distortion effects are minimized and affect slightly the momentum distribution. Therefore it should be possible to extract the effective number of α clusters in the nuclei. We conclude that ($p,p\alpha$) reactions with high-energy protons are well suited probes for the study of α-cluster structures.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Valladas and Professor M. Froissart. This experiment could not have been done without their support and their constant interest. We must also express our thanks to the whole CEA Synchrotron Division for facilities put at our disposal and, in particular, Dr. B. Thevenet for invaluable help during the experiment.

---

*Work supported by the CEA and the I N2 P3.

[1]M. Danos and V. Gillet, Phys. Lett. 34B, 24 (1970).
[2]J. C. Faivre *et al.*, Phys. Rev. Lett. 24, 1188 (1970).
[3]A. N. James and H. G. Pugh, Nucl. Phys. 42, 441 (1963).
[4]C. Ruhla *et al.*, Phys. Lett. 6, 282 (1963).
[5]B. Gottschalk and S. L. Kannenberg, Phys. Rev. C 2, 24 (1970).
[6]N. S. Chant and P. G. Roos, Phys. Rev. C 15, 57 (1977).
[7]D. Bachelier *et al.*, Nucl. Phys. A 268, 488 (1976).
[8]P. G. Roos *et al.*, Phys. Rev. C 15, 69 (1977).
[9]R. Anne *et al.*, in *Proceedings of the Conference on Clustering Phenomena in Nuclei*, (University of Maryland, College Park 1975), p. 309.
[10]R. Anne *et al.*, J. Phys. C 5, 129 (1975).
[11]G. Charpak *et al.*, Nucl. Instum. 97, 377 (1971).
[12]B. Fagerstrom *et al.*, Nucl. Instum. 91 125 (1971).