more firmly, the ^{87}Kr β spectrum was fitted with two different shape factors for the β group feeding the 846-keV level. The group was fitted with a first-forbidden-unique shape factor, as is appropriate for the $\frac{1}{2}^-$ assignment, in all of the fits given in Table I. In particular, the fit with no intensity constraints had a least-squares sum of 155 with the unique shape factor. With a statistical shape factor for this group the least-squares sum was 194. This 25% increase in the least-squares sum is rather substantial for a β group with only 5% of the total intensity. However, the Fermi plot obtained after subtracting the higher-energy groups from the spectrum had enough statistical fluctuations to prevent a distinction between the unique and statistical spectrum shapes. Thus the identification of the 846-keV level as $\frac{1}{2}^-$ by direct observation of the first-forbidden-unique shape of the β group could not be made with our data. The $\frac{1}{2}^-$ assignment could not therefore be firmly established by our measurement; however, the better fit obtained with the unique shape does give some support to the assignment.

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Quasifree ($p, p\alpha$) Scattering on ^{6}Li, ^{24}Mg, ^{28}Si, ^{40}Ca, ^{140}Ce, and ^{232}Th at 156 MeV

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Knockout of α particles by 156-MeV protons from ^{6}Li, ^{24}Mg, ^{28}Si, ^{40}Ca, ^{140}Ce, and ^{232}Th has been used to investigate the A dependence of α clustering in nuclei. Protons and α particles were detected in coincidence under conditions of quasifree scattering. Corresponding reaction cross sections were measured. Cross sections for ^{24}Mg and ^{40}Ca were found to be about 2 orders of magnitude lower than for ^{6}Li. The cross section for ^{28}Si was found to be about 3 times lower than that for ^{24}Mg and ^{40}Ca. Upper limits of the integrated cross sections for ^{140}Ce and ^{232}U are still compatible with a $A^{2/3}$ dependence of the α knockout process.

I. INTRODUCTION

The quasifree ($p, p\alpha$) reaction provides a convenient approach for investigating the parentage of α clusters in target nuclei. Recent interest in this information is due to its relevance to the new α-particle models[1] and also to the question of existence of quartets in nuclear structure.[2]

The problem of four-nucleon structures in nuclei is also being approached by means of reactions such as (d, ^{6}Li), (^{3}He, ^{7}Be), (^{12}C, ^{16}O), etc.[3] However, the relative complexity of the projectiles and the outgoing particles, and of the reaction mechanism, complicates the interpretation of such data. By comparison, the quasifree ($p, p\alpha$) knockout can be considered a "clean" process, directly interpretable in terms of the parentage of α-particle structures in target nuclei within the framework of impulse approximation.[4]

Unfortunately, the ($p, p\alpha$) cross sections are generally low and consequently the experiments are not easy to perform. No coincidence data were available, to our knowledge, on the quasifree ($p, p\alpha$) knockout process for targets having

Z greater than 8.[5] The aim of the present experiment was to investigate targets with *Z* higher than used heretofore, and thus to initiate the investigation of the *A* dependence of α clustering in nuclei. With exception of the ^{6}Li reference target,[6] the targets chosen for the present investigation were all of the even-even type: ^{24}Mg, ^{28}Si, ^{40}Ca, ^{140}Ce, and ^{232}Th. The purpose of this measurement was to gain a glimpse of the trends of the α parentages across the Periodic Table, rather than to achieve definitive statistical accuracy.[7]

II. EXPERIMENTAL SETUP

The experiment was carried out by means of the "stochastically" extracted 156-MeV beam of the Orsay synchrocyclotron. The beam intensity had to be limited to about 10 nA to avoid pileups and to keep accidental coincidences down to a tolerable value. Accidental coincidences constituted the major limiting factor and are the prime cause of the statistical uncertainties of the data.

Two opposing factors have influenced the choice of kinematic conditions of the measurements. Because the cross section decreases rapidly as the proton angle increases, and because the accidental coincidence rates become prohibitively high for small α angles, the proton angle had to be chosen as small as possible. On the other hand, for small proton angles the energy of the knocked out α cluster becomes too small. As a compromise, the proton angle was fixed at 60°. In this way, the mean cutoff energy of the detected α particles of ~18 MeV was achieved. This implies that an excitation energy of ~15 MeV in the residual nuclei could be reached.

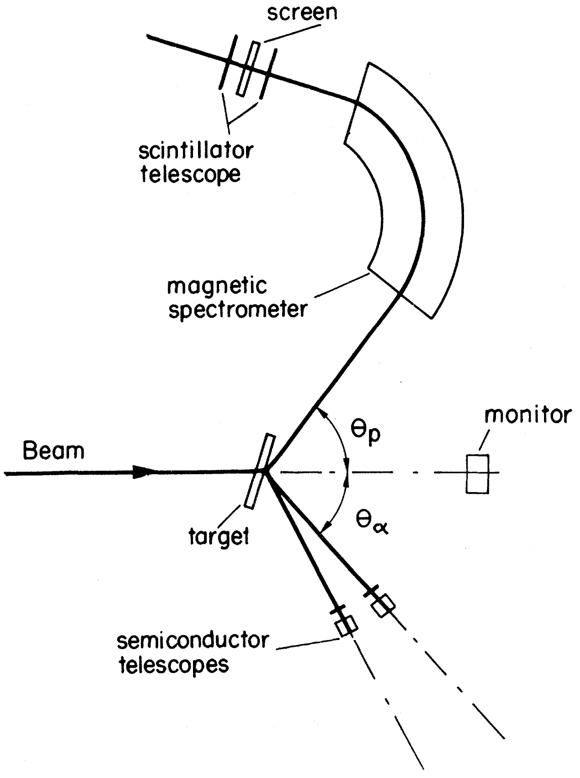

FIG. 1. Schematic diagram of the experimental arrangement. The magnetic spectrometer is a 120° bending magnet with effective radius of 170 cm.

The energy and the angle of the quasifree scattered protons were fixed and matched for zero-recoil conditions. Protons were identified and detected by a magnetic spectrometer followed by two coincident scintillation counters placed one behind the other and separated by an absorber which would stop particles less penetrating than protons. The scintillators of this system were plastic slabs 2 mm thick. The proton pulses served as coincidence gates for counting of the properly delayed α pulses. The α pulses originated in a ΔE-E solid-state particle-identification system placed at an angle corresponding to zero-recoil momentum of the residual nucleus. The corresponding solid angle was 1.26×10^{-3} sr. A second α identification system was located 10° off towards higher angles from the first α telescope. It also operated in coincidence with the proton pulses. The α telescopes were composed of 200-μ-thick silicon surface-barrier ΔE detectors and 1-mm-thick silicon surface-barrier *E* detectors cooled by Peltier cells. The accidental counting rate was recorded by delaying the α pulses additionally by three rf periods of the machine. The over-all resolving time of the proton-α coincidences was on the order of 70 nsec.

Data were processed "on line" by means of an IBM 360-50 computer which assured proper identification of α particles on 256×256 ΔE-E matrices. The two-dimensional printout of the true and the accidental coincidences could be obtained at any time for either of the two α telescopes. The layout of the experiment is shown in Fig. 1.

TABLE I. Specifications of targets. All targets were self-supporting.

Target	Enrichment (%)	Thickness (mg/cm^2)
^{6}Li	99.3	9.6
^{24}Mg	99.6	15.4
^{28}Si	Natural (92.2)	12.1
^{40}Ca	Natural (96.9)	12.6
^{140}Ce	Natural (88.5)	28.6
^{232}Th	Natural (100)	79.1

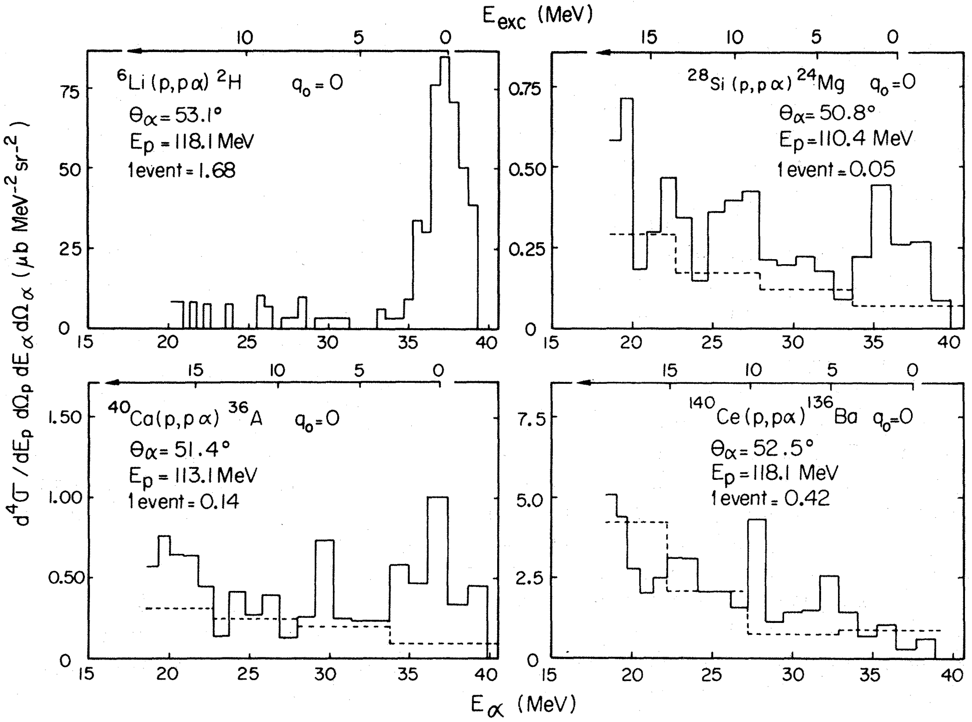

FIG. 2. Coincidence spectra of $d^4\sigma/dE_p d\Omega_p dE_\alpha d\Omega_\alpha$ versus E_α (and versus excitation energy E_{exc} of the recoil nucleus) for ^{6}Li, ^{28}Si, ^{40}Ca, and ^{140}Ce corresponding to a recoil of $q=0$ of the residual nucleus in its ground state. The proton lab angle was $\theta_p = 60°$. The corresponding proton energy E_p is indicated next to each spectrum along with the corresponding α angle θ_α. Calibration for one event is given in units μb MeV^{-1} sr^{-2}.

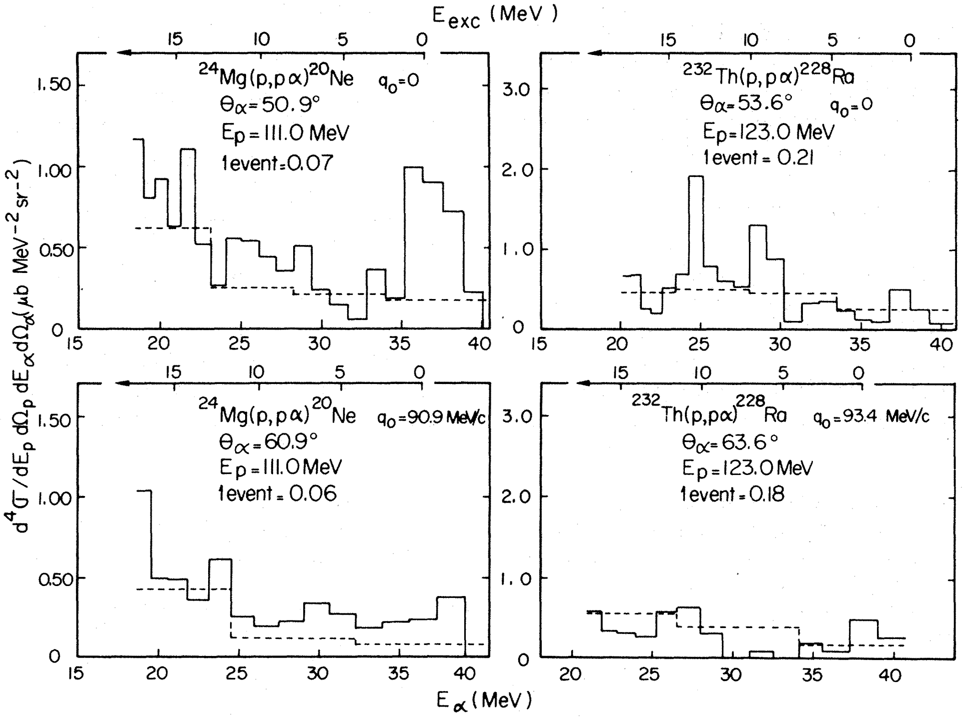

FIG. 3. Coincidence spectra of $d^4\sigma/dE_p d\Omega_p dE_\alpha d\Omega_\alpha$ vs E_α (and vs E_{exc}) for ^{24}Mg and ^{232}Th. The top and bottom spectra correspond to recoil momenta of $q=0$ and $q=91$ MeV/c, respectively. The $q=0$ and $q=91$ MeV/c conditions apply to the residual ground state only.

The ^{6}Li(p, $p\alpha$) reaction[6] served as a control experiment for lining up the apparatus and for calibration of energies and time delays. Moreover, measurements on this reaction were extended to new kinematic conditions so that complementary information on this reaction was obtained.

The properties of targets used in this experiment are listed in Table I. The half-thicknesses of targets were chosen to give an energy loss on the order of 1.2 MeV for 32-MeV α particles, except for ^{232}Th, where it was 3.5 MeV.

III. EXPERIMENTAL DATA

Sample spectra of $d^4\sigma/dE_p d\Omega_p dE_\alpha d\Omega_\alpha$ versus E_α are shown in Figs. 2 and 3. Spectra are shown for ^{6}Li, ^{24}Mg, ^{28}Si, ^{40}Ca, ^{140}Ce, and ^{232}Th. All of the spectra in Fig. 2 and the two top spectra in Fig. 3 correspond to the $q=0$ recoil condition. The two bottom spectra in Fig. 3 were taken with the second α telescope, corresponding to a recoil momentum of $q \sim 91$ MeV/c. The $q=0$ and the $q=91$ MeV/c conditions apply to the residual ground state only. Higher excitations lead to somewhat different recoil momenta.

Integrated values of the cross sections are listed in Table II. The observational limit for the ^{140}Ce and the ^{232}Th measurements is poorer than for the first four targets for the following reason. A heavy target chosen so as to give the same energy loss for α particles as a given light target, will contain fewer nuclei per cm^2 than the light target. The counting rate for a given differential cross section would then be smaller for the heavier target, giving rise to a larger statistical error.

IV. DISCUSSION

Our data confirm the exceptionally high $\langle \alpha + d \,|\, ^6\mathrm{Li}\rangle$ parentage. The cross section for the ^{6}Li(p, $p\alpha$)d reaction is almost 2 orders of magnitude higher than that for the s-d nuclei investigated. The peak in the ^{6}Li(p, $p\alpha$)d spectrum in Fig. 2 corresponds to a bound recoiling deuteron. The tail on the left-hand side of this peak should correspond to the ^{6}Li(p, $p\,\alpha$)pn reaction channel. The ^{6}Li(p, $p\alpha$) reaction cross section was measured at $\theta_p = 45°$ and $\theta_p = 60°$. The corresponding cross sections are 0.827 ± 0.065 and 0.224 ± 0.023 mb/sr^2 MeV, respectively. When compared to the elastic $p+\alpha$ scattering data[8] for these angles (corrected for the difference in incident energy and proton momentum transfer), the ratio of quasielastic cross sections for 45 and 60° is lower by a factor of about 0.7 than the same ratio in the elastic case. At $q=91$ MeV/c the ^{6}Li(p, $p\alpha$)d cross section becomes very small. At 45°, the p-α angular correlation falls to half its maximum value in less than $\Delta\theta_\alpha = 5°$. Half of the maximum value is also reached at about 3.5 MeV off the $q=0$ condition which occurs at $E_p = 132.37$ MeV. Our data thus confirm that the momentum distribution of α clusters is narrower in ^{6}Li than in other nuclei.[4-6]

For each of the s-d nuclei investigated, we see a peak in the ground-state region of the residual nucleus. Besides the ground state, this peak may involve excitations of up to 3 or 4 MeV in the residual nucleus. This peak is particularly prominent in the s-d nuclei studied, in which the outermost neutrons and the outermost protons forming the α particle belong to the same outer shell. The importance of higher excitations may be somewhat different than the present data suggest: The kinematic constraints imposed by the positioning of the detectors insured $q=0$ only for the ground state of the recoil nucleus. The ^{28}Si target shows a cross section which is about 3 times smaller than that of ^{24}Mg or of ^{40}Ca. This implies that the parentage $\langle \alpha + \Sigma\, ^{24}\mathrm{Mg}\ (\text{lower states}) \,|\, ^{28}\mathrm{Si}\ (\text{g.s.})\rangle$ is substantially smaller than the corresponding coefficients for the other two nuclei. This is not in disagreement with recent ideas on the α structure of s-d nuclei.[9]

The counting rate of the second p-α coincidence system (10° off the $q=0$ condition) was of the order of 40% of the first system. This allows the conclusion that the contribution to the knockout pro-

TABLE II. Integrated cross sections in μb MeV^{-1} sr^{-2} corresponding to (a) low-lying states of the residual nucleus with excitation energies E_{exc} from 0 to 5 MeV; (b) states of the residual nucleus with E_{exc} from 5 to 15 MeV. The conditions $q=0$ and $q=91$ MeV/c hold only for the ground-state transition. For ^{140}Ce and ^{232}Th targets, integration was carried out over E_{exc} from 0 to 15 MeV.

Target		^{6}Li	^{24}Mg	^{28}Si	^{40}Ca	^{140}Ce	^{232}Th
$q=0$	(a)	224 ± 23	3.1 ± 0.5	1.1 ± 0.3	2.9 ± 0.8	8.4 ± 4.0	7.5 ± 7.2
	(b)		2.1 ± 0.6	1.4 ± 0.5	1.2 ± 0.9		
$q \simeq 91$ MeV/c	(a)		1.0 ± 0.4	≤ 0.6	1.2 ± 0.5	≤ 2.3	≤ 1.5
	(b)		1.5 ± 0.7	≤ 0.4	1.6 ± 1.0		

cess of α particles of $L=0$ is considerable.

The variation of the cross section for the α-knockout process between our group of s-d target nuclei and the two heavier target nuclei is still compatible with an $A^{2/3}$ dependence, if account is taken of the statistical limits of this experiment. However, such a simple surface dependence provides only a very rudimentary description of the knockout process. It is quite clear that experimental results with improved statistics should be compared with detailed parentage calculations taking into account the different shells to which the outer neutrons and protons may belong.

An interesting question concerns the existence of quasifree processes involving the knockout of α particles from inner shells of nuclei: The observation of such a process would have direct bearing on the internal structure of nuclei. This type of experiment may be within the reach of the high-resolution medium-energy accelerators that are just now becoming fully operational.

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