(α, 2α) Reaction on ^{9}Be at 42.8 and 49.2 MeV and on ^{16}O at 49.2 and 52.5 MeV

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The (α, 2α) reactions on ^{9}Be at 42.8 and 49.2 MeV and ^{16}O at 46.0 and 52.5 MeV have been studied in order to test the validity of the impulse approximation. The experimental data are consistent with this approximation, but the over-all agreement is much worse than in the case of the (α, 2α) reaction on ^{6}Li.

Quasielastic scattering experiments $A(a, ab)B$ are generally considered to provide the most direct proof of the existence of clusters in nuclei. The theoretical analysis of such experiments is usually made with the plane-wave impulse approximation. In this case, if one supposes spinless particles, the cross section can be factored and written as

$$\frac{d^3\sigma}{d\sigma_a d\sigma_b\, dE_a} = N_{\rm eff}\, \mu\rho(q)\left(\frac{d\sigma}{d\Omega}\right)_{ab}. \qquad (1)$$

$N_{\rm eff}$ is the effective number of clusters b in the target nucleus. It can be calculated by assuming a theoretical model (shell model, for instance) or it can be considered as a parameter whose value can be deduced from the experimental results. μ is a kinematical factor coming from the integration over a phase-space domain determined by the experimental conditions. $\rho(q)$ is the impulse distribution of the cluster b in the target nucleus; it is the square of the Fourier transform of the wave function describing the relative motion of B and b in the target nucleus. $(d\sigma/d\Omega)_{ab}$ is the scattering cross section (a, b) taken off the energy shell. Another approximation can be made by taking this cross section on the energy shell, with the relative energy of the particles a and b taken either before the reaction (E_i form) or after the reaction (E_f form).

Recent experiments on the reactions ^{6}Li(α, 2α)[1,2] and ^{6}Li(p, $p\alpha$)[1] at various energies have shown that the cross section given by formula (1) is in agreement with the experimental results, and that the $\alpha\alpha$ scattering cross section can be taken on the energy shell in the E_f form.[2]

As we did for ^{6}Li, we thought it would be interesting to study the (α, 2α) reaction on heavier targets, and to use the $\alpha\alpha$ scattering resonance at 19.8 MeV (c.m.) as a test of the reaction mechanism. We did these experiments on ^{9}Be at 42.8 and 49.2 MeV and on ^{16}O at 46.0 and 52.5 MeV.

The experiments have been made with the isochronous cyclotron of the I.S.N. at Grenoble. The energies of the incident particles have been measured with an uncertainty of 200 keV. The ^{9}Be target, 2.5 mg/cm^2 thick, was self-supporting, while the ^{16}O target was made of 1.9-mg/cm^2-thick quartz.

The α particles were detected, in a symmetric and coplanar geometry, in coincidence with particle identification on one channel. The experimental setup was identical to the one already described.[3]

To determine the impulse distribution of the cluster, we used a method of angular distribution (for each pair of detection angles, we took into account the events for which both α particles had the same energy, q being then colinear with the incident particle direction, and the $\alpha\alpha$ scattering being always at 90° c.m.) and a method of energy distribution (for a pair of angles, all the events lying on the kinematic quasielastic region are taken into account; this allows an exploration of the different values of q).

If one chooses an analytical form for the wave function of the α-core relative motion, formula (1) permits one to obtain from the experimental results spectroscopic information on the cluster structure of the target nucleus. We chose two forms for this wave function:

(i) We assumed that the target nucleus was described by the harmonic-oscillator shell model; the relative motion is then also described by an harmonic-oscillator function whose quantum numbers N and L can be determined. The comparison of the experimental results with formula (1) is then made by adjustment of the harmonic-oscillator parameter which describes the relative motion. This allows the definition of the isolation coefficient $x = \beta/\alpha^4$ where α and β are the parameters of the harmonic oscillator, respectively, for the shell-model description of the target and for the relative motion.

(ii) We then assumed that the clustering probability was zero when the cluster-core distance was smaller than a radius $R_c = 1.5\, A^{1/3}$ fm and that for $r > R_c$ the relative motion was described by a spherical Hankel function $h_l(iKr_{bc})$, where K^2

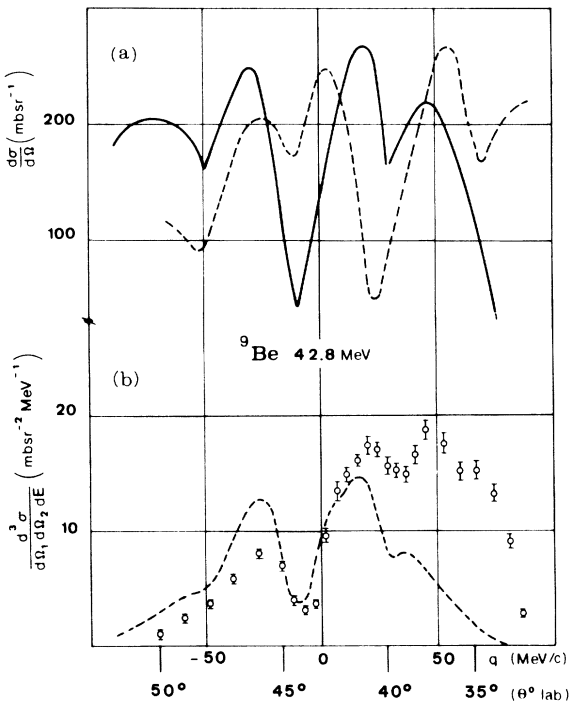

FIG. 1. (a) Free $\alpha\alpha$ scattering cross section. Solid line: E_f form, dashed line: E_i form. (b) ($\alpha, 2\alpha$) reaction cross section, angular-distribution method. Dashed line: best fit obtained with formula (1) and $\alpha\alpha$ scattering cross section in the E_f form.

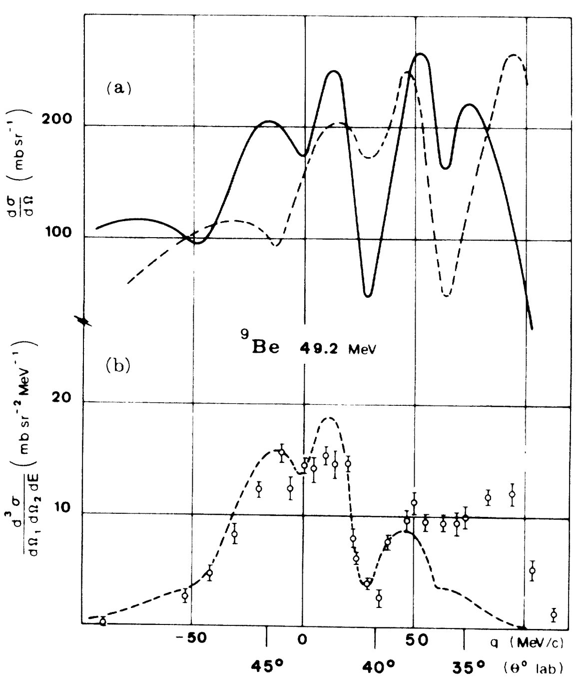

FIG. 2. (a) Free $\alpha\alpha$ scattering cross section. Solid line: E_f form, dashed line: E_i form. (b) ($\alpha, 2\alpha$) reaction cross section, angular-distribution method. Dashed line: best fit obtained with formula (1) and $\alpha\alpha$ scattering cross section in the E_f form.

$=(2m/\hbar^2)B$, where B is the cluster-core binding energy. The analytical forms of these wave functions have been given elsewhere.[2]

Figures 1(b), 2(b), 3(b), and 4(b) show the results obtained, respectively, on ^{9}Be at 42.8 and 49.2 MeV and on ^{16}O at 46.0 and 52.5 MeV with the angular-distribution method. Figures 1(a), 2(a), 3(a), and 4(a) show the $\alpha\alpha$ scattering cross sections with the same abscissa, in the E_i and E_f forms.

One can see that the general behavior of the free (α, α) scattering cross section, if taken in the E_f form, and in particular the 19.8-MeV resonance, can be found in the quasielastic cross section obtained for ^{9}Be at 42.8 and 49.2 MeV. The results are more ambiguous for ^{16}O; there is also a very deep minimum in the free $\alpha\alpha$ cross section at 11.5 MeV, and the energy difference between the two minima is close to the binding energy of an α particle in ^{16}O, which is the energy difference between forms E_i and E_f. It seems, however, that one can choose the E_f form.

One can say then that the incident α particle gives enough kinetic energy to break the target nucleus, and that a free scattering happens after-

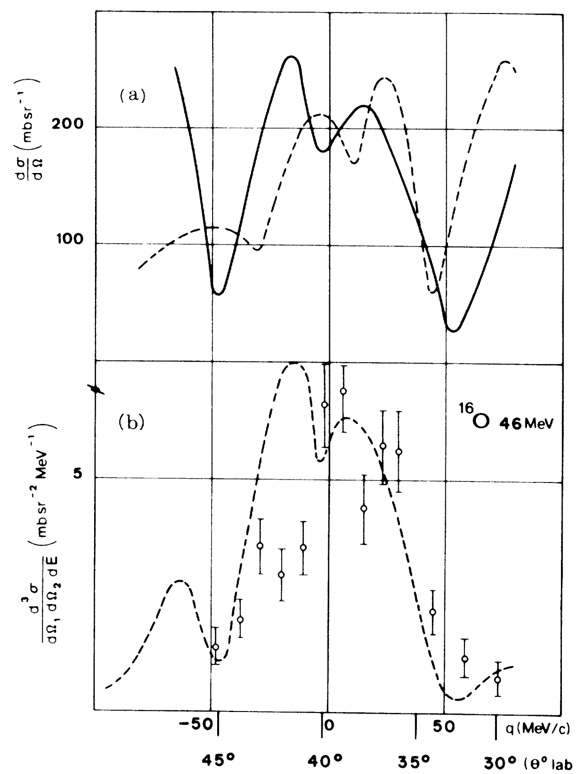

FIG. 3. (a) Free $\alpha\alpha$ scattering cross section. Solid line: E_f form, dashed line: E_i form. (b) ($\alpha, 2\alpha$) reaction cross section, angular-distribution method. Dashed line: best fit obtained with formula (1) and $\alpha\alpha$ scattering cross section in the E_f form.

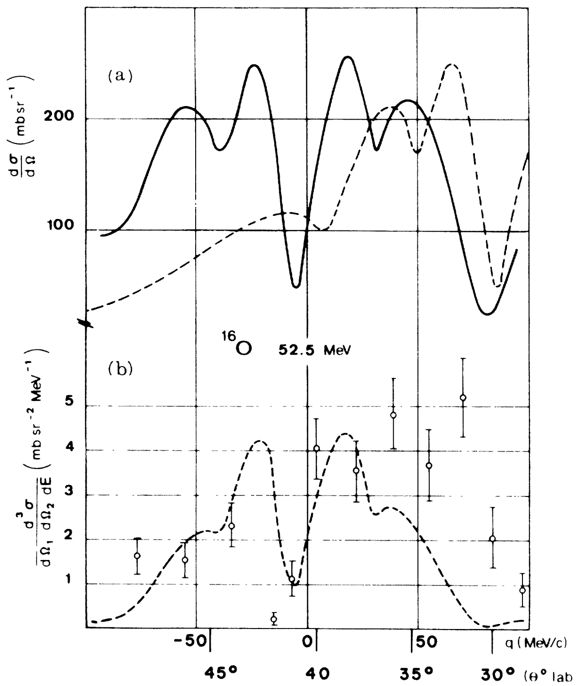

FIG. 4. (a) Free $\alpha\alpha$ scattering cross section. Solid line: E_f form, dashed line: E_i form. (b) $(\alpha, 2\alpha)$ reaction cross section, angular-distribution method. Dashed line: best fit obtained with formula (1) and $\alpha\alpha$ scattering cross section in the E_f form.

wards. Furthermore, one can see that the cross sections for the large angles are usually lower than for the small angles, but the experimental distributions reflect the shape of the $\alpha\alpha$ scattering curve.

The curves shown with the experimental points are calculated using formula (1), and taking the $\alpha\alpha$ cross section on the energy shell (in the E_f form). The agreement is not satisfactory and one cannot obtain from the fit any spectroscopic information. Similar results are obtained by taking either a Hankel function or a harmonic-oscillator function to calculate $\rho(q)$.

Results obtained by the energy-distribution method on ^{9}Be and ^{16}O are shown in Figs. 5 and 6. The curves have been calculated with formula (1), in the E_f form, with both analytical forms mentioned for $\rho(q)$.

Table I shows the spectroscopic information one can deduce from this analysis; we also show the results obtained for ^{9}Be at 55 MeV in a previous experiment.[3] In the case of ^{9}Be, one can see that the values of the parameters obtained at various energies are within the experimental uncertainties. The values of N_{eff} are, however, lower than the values given in the literature [N_{eff} varies from 0.25 for the $(p, p\alpha)$ reaction at 57 MeV[5] to 0.065 for the $(p, p\alpha)$ reaction at 155 MeV[6]]. The values

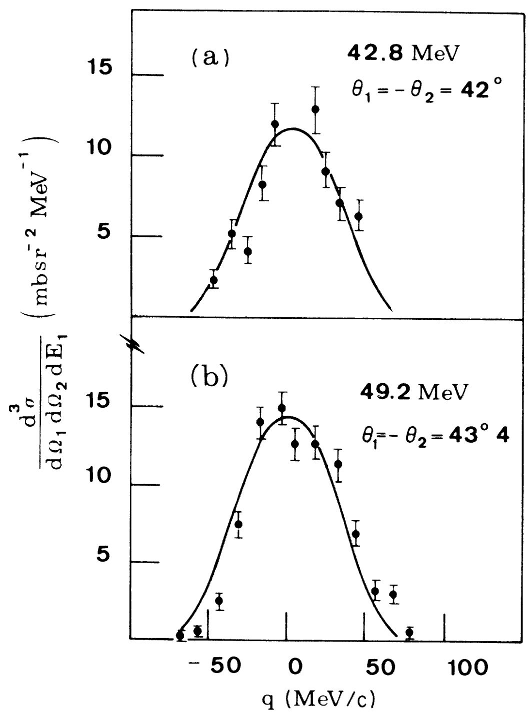

FIG. 5. ^{9}Be$(\alpha, 2\alpha)$ reaction cross-section, energy-distribution method. Solid line: best fit obtained with formula (1) and the $\alpha\alpha$ scattering cross section in the E_f form.

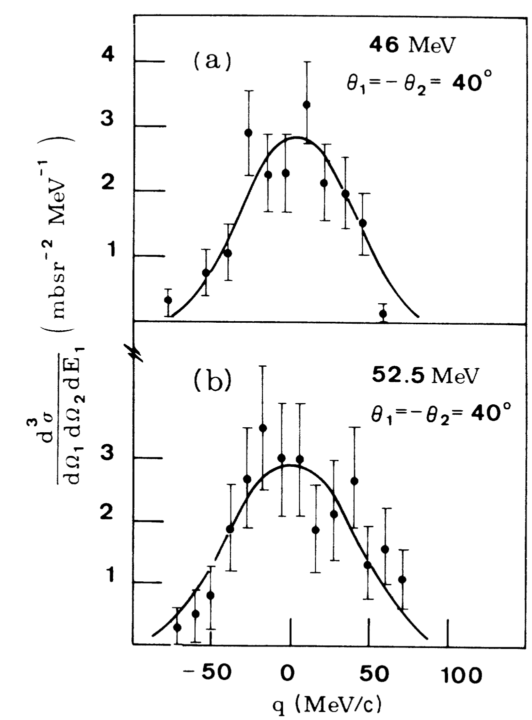

FIG. 6. ^{16}O$(\alpha, 2\alpha)$ reaction cross section, energy-distribution method. Solid line: best fit obtained with formula (1) and the $\alpha\alpha$ scattering cross section in the E_f form.

TABLE I. Spectroscopic information deduced from the analysis of the $(\alpha, 2\alpha)$ reaction on ^{9}Be and ^{16}O.

Target nucleus	Energy (MeV)	Angle $\theta_1=-\theta_2$ (deg)	Isolation parameter x	N_{eff} (H.O.) (harmonic oscillator)	N_{eff} (Hankel function)
^{9}Be	42.8	42	0.35	0.025	0.02
	49.2	43.4	0.40	0.03	0.02
	55	43.6	0.50	0.055	0.03
^{16}O	46	40	0.5	0.03	0.03
	52.5	38	1.0	0.03	0.015

obtained for the isolation parameter show a well-marked cluster structure ($x<0.5$). In the case of ^{16}O, the isolation parameter varies by a factor of 2. A value close to 1 seems reasonable, meaning that ^{16}O does not need a special cluster description.

The results obtained using the angular-distribution method and by the energy-distribution method seem quite different. In the latter method, the $\alpha\alpha$ scattering cross sections are almost constant, the scattering angle and the relative energy in the center of mass varying in a very small range (for instance, in the case of ^{9}Be at 42.8 MeV, when q varies from 0 to 100 MeV/c, $\theta_{c.m.}$ varies from 90 to 87.4° and $E_{c.m.}$ varies from 17.43 to 17.67 MeV). This method has then the advantage of minimizing the influence of the variations of the $\alpha\alpha$ cross sections when one makes the approximation of taking the cross sections on the energy shell; in the angular-distribution method, on the contrary, the $\alpha\alpha$ cross sections vary greatly. Jain *et al.*[1] reach the same conclusion when they remark that the shapes of the impulse distribution $\rho(q)$ obtained in $(p, p\alpha)$ and $(\alpha, 2\alpha)$ reactions are similar when the analysis is made by an energy-distribution method, but they are different from those obtained by the angular-distribution method on the $(\alpha, 2\alpha)$ reaction.

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