Quasi-Elastic p-a Scattering in C^{12}

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Quasi-elastic $p-\alpha$ scattering experiments, such as the (α, 2α) reaction, in the medium and high energy domains, can be used to extract information on α-cluster states in the nucleus.

Very little work has been done on this subject since the original experiment which led P. Cuër to suppose such nuclear substructures in the nucleus.[1] The few experiments that have been carried out are based on the use of nuclear emulsions.[2] Very recently, however, two experiments have been done with electronic apparatus; the first by M. Riou *et al.*[3] on Li^6, Li^7, and Be^9, and the second by H. G. Pugh *et al.*[4] on C^{12}; both groups working with 155-MeV protons.

These electronic methods are ideal for the measurement of coplanar events, but the small cross section of this reaction leads to the disadvantage of requiring a long beam time; and furthermore, such methods give no information on the noncoplanar events.

During the experiment on the C^{12} (p, sp) B^{11} reaction[5] with the propane bubble chamber and the 123-MeV proton degraded beam from the Orsay synchrocyclotron, we analysed the kinematics of all two-branch events, which include C^{12} (p, $p\alpha$) Be^8, proving the existence of this latter reaction.[6]

KINEMATICAL ANALYSIS

We consider a collision between an incident proton and an α particle existing as a cluster-state in the C^{12} nucleus.

The suffixes 0, p, α, and R are used, respectively, to designate the incident and scattered protons, the target α particle and the recoil Be^8 nucleus.

Energy conservation requires that:

$$E_0=E_p+E_\alpha+E_R+E_{L\alpha},$$

$$E_{L\alpha}=Q+E_x. \tag{1}$$

Where $E_{L\alpha}$, E_x, and Q represent, respectively, the binding energy, the excitation energy of the final state in Be^8, and the Q value of the reaction.

The conservation of momentum can be written:

$$\mathbf{p}_0=\mathbf{p}_p+\mathbf{p}_\alpha+\mathbf{p}_R, \tag{2}$$

where, using the impulse approximation,

$$\mathbf{p}_R=-\mathbf{p}, \tag{3}$$

the momentum $\mathbf{p}$ being that of the α particle before collision.

In the experiment described here, $\mathbf{p}_0$, $\mathbf{p}_p$, and $\mathbf{p}_\alpha$ are obtained directly for each event, $\mathbf{p}_R$ can be calculated, and hence $\mathbf{p}$, using the impulse approximation. This approximation, however, does not seem to be rigorously applicable in the energy region considered here ($\bar{E}_0=85$ MeV) with C^{12}.

All the 2-branch events have been analysed kinematically in each case, one of the two emitted particles is considered to be p, d, t, He^3, or α. The (p, $p\alpha$) reaction is followed by a breakup of the Be^8 nucleus into two α particles, which is a 4-branch event. Most of the events analysed in the experiment are, however, two-branch, this is due to the fact that the secondary breakup α's are generally emitted with low energy which renders their detection difficult. A small number of 3-branch and 4-branch events, which can be classified as (p, $p\alpha$) reactions by $E_{L\alpha}$ have however been found. These have been taken into account in the estimation of the cross section.

EXPERIMENTAL RESULTS

(*1*) $E_{L\alpha}$. The $E_{L\alpha}$ distribution of all 2-branch events, except those classified as C^{12} (p, $2p$) B^{11} with a p-shell proton from C^{12}, shows a fairly pronounced peak at 7.5 ± 4 MeV and another broaden peak at 15–25 MeV. The first peak corresponds to the (p, $p\alpha$) reaction which leaves the residual nucleus in the ground or first excited state ($E_x\approx3$ MeV). The second peak might correspond to an excited state at about 11 MeV in the residual nucleus. We have limited our investigation to those events belonging to the first peak only.

Up to the present we have carried out only kinematic analysis, in which certain events can be ascribed to two or more different reactions. This ambiguity should be resolved in the near future through the use of a microdensitometer specially designed for the measurement of track densities.

(*2*) *Coplanarity.* The observed events are, for the most part, coplanar, as are the (p, $2p$) events. About 70% of the cases have an angle of coplanarity $\epsilon\leq30°$, presenting thus the characteristics of direct quasi-elastic scattering.

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[2] P. Cuër, J. Combe, and A. Samman, Compt. Rend. **240**, 75 (1955). A. Samman and P.Cuër, J. Phys. Radium **19**, 13 (1958). M. Gauvin, R. Chastel, and L. Vigneron, Compt. Rend. **253**, 257 (1961). M. Gauvin and R. Chastel (to be published).
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[6] T. Yuasa, Phys. Letters **8**, 318 (1964).

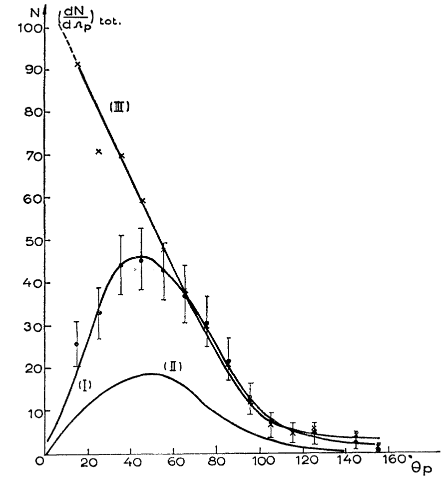

FIG. 1. Angular distribution and $d\sigma/d\Omega_p$ distribution of scattered protons. I. Angular distribution for all events. II. Angular distribution for coplanar events ($\epsilon \leq 30°$). (Scale $\frac{1}{2}$). III. $d\sigma/d\Omega_p$ distribution (arbitrary units).

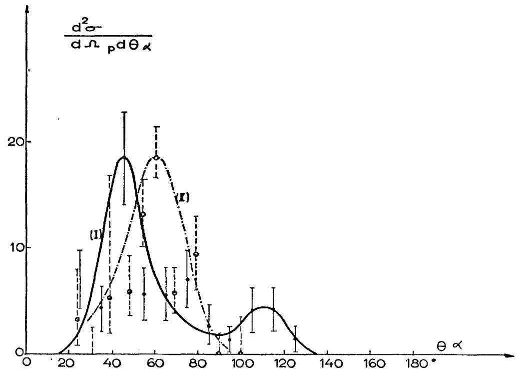

FIG. 3. Angular distribution of emitted α particles for those events in which $\theta p = 45° \pm 5°$. I. Present results ($\epsilon \leq 30°$). Points marked with O. Results obtained by Pugh *et al.* for $E_0 = 155$ MeV (normalized at the peak.) II. Theoretical values obtained by Sakamoto for the experimental conditions of Pugh *et al.* (normalized at the peak).

(3) *Angular distribution of scattered protons.* Figure 1 shows the natural angular distribution of scattered protons. (Curve I and curve II; curve I for all events, and curve II for those coplanar events only having $\epsilon \leq 30°$) (scale $\frac{1}{2}$). Also shown in Fig. 1 is the differential cross section $d\sigma/d\Omega_p$ distribution (curve III, arbitrary units). The maximum in curve III occurs for $\theta_p = 0$ (where θ_p is the angle between the incident and scattered protons), as in the case for elastic p–α scattering.

(4) *Angular distribution of emitted α particles.* The angular distribution of the emitted α particles should be correlated with that of the scattered protons if the collision is supposed to be elastic or quasi-elastic. The differential cross sections $d^2\sigma/d\Omega_p d\theta_\alpha$ have been obtained; their distribution for all events is shown in Fig. 2, curve I (arbitrary units). The curve calculated for elastic $p-\alpha$ scattering on the basis of the proton angular distribution of Fig. 1 is shown also in Fig. 2 (curve II, normalized at the peak). It will be remarked that the maximum is displaced towards smaller θ_α, and that a second small peak appears for $\theta_\alpha \geq 90°$ in our results. The same tendencies have been observed in the distribution for those events in which $\theta_p = 45° \pm 5°$ and $\epsilon \leq 30°$ (Fig. 3, curve I), compared with the results obtained by H. G. Pugh *et al.* (Fig. 3, points marked with O) for $E_0 = 155$ MeV and the values calculated by Y. Sakamoto[7] for the same energy using the harmonic oscillator model and distorted wave functions assuming α-clusters (Fig. 3, curve II) (the 3 curves are normalized at the peak).

(5) *Angular correlation distribution of the scattered protons and emitted α's.* The $d^2\sigma/d\Omega_p\, d(\theta_p+\theta_\alpha)$ distribution for events for which $\epsilon \leq 30°$ is shown in Fig. 4, curve I, as well as the calculated distribution for elastic $p-\alpha$ scattering for all events assuming the proton

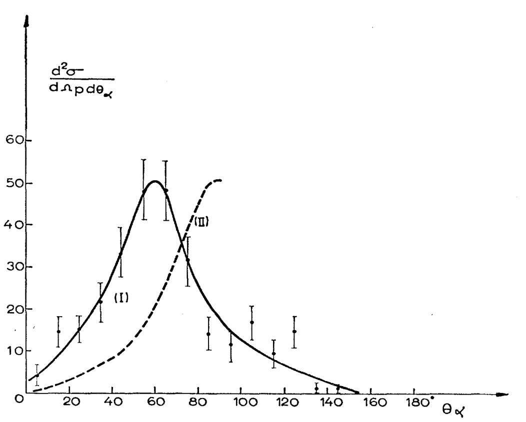

FIG. 2. Angular distribution of emitted α particles. I. Experimental results. II. Calculated distribution for elastic $p-\alpha$ scattering using the $d\sigma/d\Omega_p$ curve of Fig. 1. (normalized at the peak.)

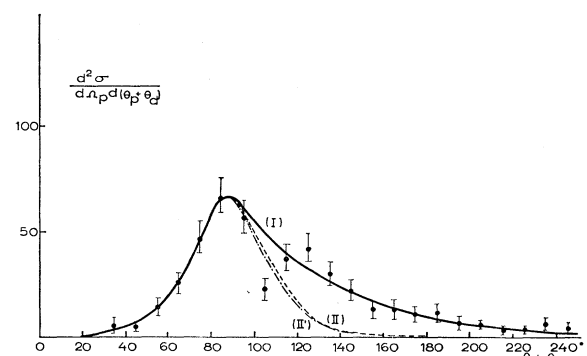

FIG. 4. $d^2\sigma/d\Omega_p d(\theta_p+\theta_\alpha)$ distribution. I. Present results for coplanar events ($\epsilon \leq 30°$). II. Calculated curve for elastic p–α scattering for all events assuming $d\sigma/d\Omega_p$ of Fig. 1. II'. Calculated curve for the coplanar events (all curves are normalized at $\theta_p+\theta_\alpha = 90°$).

[7] Y. Sakamoto (private communication).

angular distribution shown in Fig. 1 (curve II), and that for the coplanar events only (curve II′). All these curves show the maximum at $\theta_p+\theta_\alpha=90°$ (all curves are normalized at 90°).

The conclusion to be drawn from these results is that the C^{12} $(p, p\alpha)$ Be^8 reaction at $\bar{E}_0=85$ MeV possesses the characteristics of direct quasi-elastic scattering, though they are perhaps less pronounced than at $\bar{E}_0=155$ MeV.

(6) *Total cross section for* C^{12} $(p, p\alpha)$ Be^8 *leaving the residual nucleus in the ground or first excited state,* $\sigma_{(p,p\alpha)0}$. The total cross section $\sigma_{(p,p\alpha)0}$ has been calculated by comparison with the C^{12} $(p, 2p)$ B^{11} reaction provoked by a p-shell proton in C^{12} and in taking into account the observed 3-branch and 4-branch $(p, p\alpha)$ events.

Finally, an estimate is made of

$$\sigma_{(p,p\alpha)0}=\left(5.5\begin{matrix}+1.5\\-0.5\end{matrix}\right)\text{mb},$$

which is in reasonable agreement with the value found by preceding authors.[1,2]

The $|\mathbf{p}|$ distribution has also been studied as well as the probability for the existence of α clusters multiplied by the reducing factor of this collision in the C^{12} nucleus. Precise results, however, have not yet been obtained.

CONCLUSIONS

The preliminary experimental results from a bubble-chamber investigation of the C^{12} $(p, p\alpha)$ Be^8 reaction demonstrate the existence of direct quasi-elastic scattering of protons ($\bar{E}_0=85$ MeV), by nuclear α particles.

Discussion

PHILLIPS: I wasn't clear on what were the experimental conditions, what the requirements were for the data points plotted on the graph. In particular, one has a four-body final state here. You have, in fact, 3 alpha particles and a proton. Now to analyze the data *I* presume that you must have required that you formed the ground state of Be^8; is that correct?

RIOU: No. In these experiments you observe not only the ground state of Be^8 but also the 2+ and 4+ excited states.

PUGH: What was the energy of the alpha particles that you detected?

RIOU: We detect energies from about 10 MeV, up to 30 or 40 MeV.

PUGH: I worry very much about having such a low-energy particle. Then when one of the particles has a low energy, you worry about having a two-stage process, because then the proton has high energy, and may come from inelastic scattering. The energies were about the same in the Harwell experiment. The problem is that the cross section for p–a scattering is very low at high momentum transfers so one has to study the reaction at lower momentum transfers than one would like. It would be nice to find some experiments where this didn't happen.