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LETTERS TO THE EDITOR

POSSIBLE RELATIVISTIC EFFECT IN (p, 2p) REACTION ON LIGHT NUCLEI

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The $(p, 2p)$ reactions were usually used, first, to investigate the separation energies of protons in S and P nuclear shells and second, to find the momentum distributions of these protons inside nuclei[1]. The most common type of research was the symmetric coplanar experiment[2] in which the energies of two outgoing protons are detected at those angles which correspond to almost zero recoil momentum of the final nucleus. Theoretically, an impulse approximation was widely used[1, 2]. The obtained cross-section formula is then valid for the situation in which the incoming proton energy is much higher than the bound energy of proton moving inside the target nucleus. Usually, the off-shell effects are not taken into account and the image of the process is that of the quasi-elastic scattering. Recently it was shown[3] that the lower limit for the validity of the mentioned approximations is 300 MeV of the incident proton energy.

On the other hand the result of a recent experiment for studing the recoil nucleus distributions were published[4]. It has been found that the momenta of the recoil nucleus can be very high (up to 600 MeV/c and, perhaps, higher). One can suppose, then, that relativistic effects might considerably change the overall energy-momentum conservation laws of the incident-intranuclear proton system which undergoes the collision. That is the effect which we would like to point out.

Suppose, that the momentum distribution of a nucleon inside a nucleus is given by a function $N(\vec{k})$, $\vec{k}$ being its 3-momentum. Suppose, further, that this momentum is independent of angles, i. e. $N(\vec{k})$ is isotropic. Denoting the

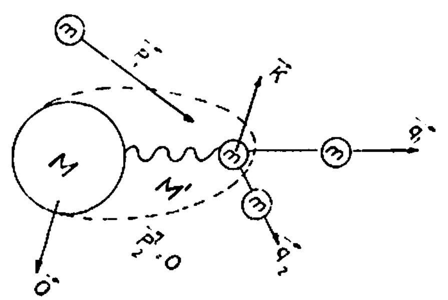

Fig. 1. The image of the quasi-elastic scattering model for $(p, 2p)$ reactions at intermediate energies.

$$p_1 + p_2 \rightarrow q_1 + q_2 + Q\,.$$

The symbols represent the particles and their 4-momenta. m is the nucleon mass, M' is the mass of the initial nucleus and M is the recoil nuclear mass.

momentum of the recoil nucleus by $\vec{Q}$, the kinematical part of the impulse aproximation tells us: $\vec{k} + \vec{Q} = 0$. Physically, this relation implies that a nucleus is a such virtually dissolving system that at the end of the reaction the additional proton and the remain nucleus have opposite momenta (Fig. 1). Accordingly, the energy conservation, supposing that the whole process is on the mass-shell, must be consistant with the above relation. For the reaction studed, using the laboratory system (supperscript L) and denoting the incident proton 3-momenta by $\vec{p}_i^{\,L}$ and its energy by ε_i^L, the nuclear proton

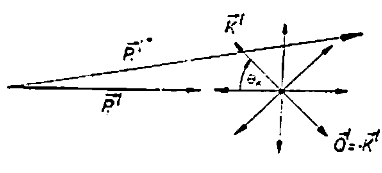

Fig. 2. The composition of the effective 3-momenta $\vec{p}_i^{\,L*}$ during the collision of two particles with 3-momenta $\vec{p}_i^{\,L}$ and $\vec{k}^L$ in a laboratory system.

3-momentum by $\vec{k}^L$ and its energy by $\varepsilon_k{}^L$, according to the Lorentz transformation one finds the following expressions for the effective total energy ($\varepsilon_L{}^*$) and momentum ($p_1{}^{L*}$) (supperscript *)

$$\varepsilon_1{}^{L*} = \frac{1}{m}(\varepsilon_k{}^L \varepsilon_1{}^L - \vec{k}^L \vec{p}_1{}^L),$$

$$\vec{p}_1{}^{L*} = p_1{}^L - \frac{k^L}{m} \mid \varepsilon_l{}^L - \frac{k^L p_1{}^L}{\varepsilon_k{}^L + m} \mid, \tag{1}$$

m being the nucleon mass (see Fig. 2).

Now, consider the final state of the reaction. Denoting by q_1 and q_2 the 4-momenta of two outgoing protons and by Q the 4-momentum of the recoil nucleus, the invariant quantity

$$\omega^2 = (q_1 + q_2)^2 = (p_1 + p_2 - Q)^2 \tag{2}$$

is modified if we write instead of p_1 ($\vec{p}_1$, ε_1) its effective values, i. e. substituting (1) into (2) we have

$$\varepsilon^{*2} = (p_1{}^* + p_2 - Q)^2 = (m + M' - M)^2 - 2\,T^*\,(M' - M) +$$

$$+ 2\,T_a{}^L\,(T^* + m + M') + 2\,p_1{}^{L*}\,Q^L\,x_{1Q}{}^{L*}, \tag{3}$$

where T^* is the abreviation for

$$T^* = T + T_N + \frac{1}{m} T\,T_N - \frac{1}{m} p_1{}^L\,k^L\,x_{1k}{}^L, \tag{4 a}$$

$$x_{1k} = \frac{(\vec{p}_1{}^L \cdot \vec{k}^L)}{|\vec{p}_1{}^L|\;|\vec{k}^L|}, \tag{4 b}$$

where T and T_N are the kinetic energy of the incoming particle and the nucleon inside the nucleus, respectivelly. In expression (3) M is the mass of the initial nucleus, M' is the mass of the final nucleus and

$$x_{1Q}{}^{L*} = \frac{(\vec{p}_1{}^{L*}\,Q^L)}{|\vec{p}_1{}^{L*}|\;|\vec{Q}^L|} = -\frac{(\vec{p}_1{}^{L*}\,\vec{k}^L)}{|p_1{}^{L*}|\;|k^L|} = -x_{1k}{}^L.$$

Also, it follows from the expression (3) that the energy and momentum conservation laws are now

$$R_0 = \varepsilon_1^{L*} + M' - Q_0^L = q_{10}^L + q_{20}^L, \tag{5 a}$$

$$\vec{R} = \vec{p}_1^{L*} - \vec{Q}_L = \vec{q}_1 + \vec{q}_2, \tag{5 b}$$

where

$$\varepsilon_1^{L*} = m + T^*; \qquad p_1^{L*} = \sqrt{T^*(T^* + 2m)},$$

and

$$Q_0 = M + T_Q^L = \sqrt{(Q^L)^2 + M^2} = \sqrt{(k^L)^2 + M^2}.$$

T_Q^L being the kinetic energy of the recoil nucleus. From the conservation laws one easily finds the total outgoing proton energy q_{10}^L and the angle θ_j^L

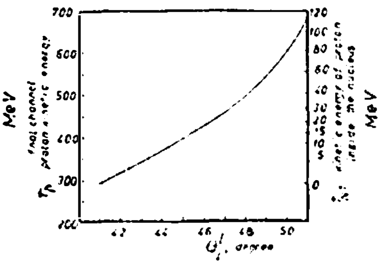

Fig. 3. Dependence of the kinetic energies T_{j0} $(j = 1, 2)$ of the final protons on θ_j^L and T_N^L in the symmetric coplanar experiment. The calculations were made for the reaction $p + {}^9Be \rightarrow {}^8Li + 2p$ at the incident proton kinetic energy $T = 600$ MeV.

in which it is detected. Taking into accont the condition for the coplanar experiment: $q_{10}^L = q_{20}^L = \theta_1^L = \theta_2^L$ we have

$$q_{j0}^L = \frac{R_0}{2}, \tag{6 a}$$

$$\cos\theta_j^L = x_j^L = \frac{R}{\sqrt{R_0^2 - 4m^2}}. \tag{6 b}$$

In Fig. 3 he have ploted the dependence of the kinetic energy of the outgoing particles on the angle of the detection θ_j for the reaction $p + {}^9Be \rightarrow {}^8Li + 2p$ at $T = 600$ MeV. As one sees from last equations, and as it is shown in Fig. 3. this effect is connected with the momentum $\vec{k}^L$ and the kinetic energy T_N^L of the proton inside the initial nucleus. We conclude, that in the framework of the impulse approximation, the relativistic effect of averall kinetic energy increase in $(p, 2p)$ reaction can be measured by detecting the greater values of the outgoing particles kinetic energy at great angles, which is accessible in a symmetric coplanar experiments.

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