4-12-1982

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Recommended Citation

T. Hennino et al. (1982). "Reaction ^{6}Li(p, Δ^{++})^{6}He At 1.04 GeV And The Δ–N Interaction". *Physical Review Letters*. Volume 48, Issue 15. 997-1000. DOI: 10.1103/PhysRevLett.48.997
https://works.swarthmore.edu/fac-physics/349

Reaction ^{6}Li(p, Δ^{++})^{6}He at 1.04 GeV and the Δ-N Interaction

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(Received 28 December 1981)

The reaction $^6\text{Li}(p,\Delta^{++})^6\text{He}$ has been studied at 1.04 GeV for transferred momenta ranging from 0.11 to 0.35 $(\text{GeV}/c)^2$. An exponential decrease of the cross section is observed. A Glauber-type calculation is presented. The possibility of extracting information on $\sigma_{\Delta N}$ and $\alpha_{\Delta N}$ is discussed.

PACS numbers: 25.40.Rb, 13.75.Cs, 21.30.+y

A novel possibility of studying the interactions of short-lived particles with nucleons was demonstrated in 1966.[1] The method analyzes the scattering of such short-lived particles on the nucleons of the same nucleus in which they were produced. The theoretical methods for interpreting this process were subsequently extended in 1967[2] and 1968.[3]

Experimentally, the production of ρ^0 and N^* on nuclei and their subsequent interactions in the same nucleus have been studied for the strictly coherent reactions only at high energies.[4] No such data exist for Δ^{++} ($I=\frac{3}{2}$) production, a process which implies a constraint of the isospin of the final state. The importance of resonances such as Δ's, and especially the 3-3 resonance at 1236 MeV, for intermediate-energy physics principally motivated our study of the reaction

$$p + {}^6\text{Li} \to \Delta^{++} + {}^6\text{He}$$
$$\Delta^{++} \to p + \pi^+$$

at 1.04 GeV,[5] at the synchrotron of the Laboratoire National Saturne.

In a two-body reaction, the measurement of the energy and angle of one of the two products completely determines the reaction. We have chosen to detect the recoil nucleus, in order to get rid of the noncoherent part of the production (breakup of the mass-6 nucleus). The experimental setup is shown in Fig. 1. The ^{6}He recoil nucleus was detected in the range $10 < E < 60$ MeV and $34° < \theta < 62°$ (in the laboratory system) by a solid-state detector telescope, thus covering at least a missing-mass interval $1170 < M < 1290$ MeV, for transfers $0.11 < |t| < 0.67$ $(\text{GeV}/c)^2$. In addition, to overdetermine the reaction, a scintillator hodoscope was set up in coincidence with the ^{6}He

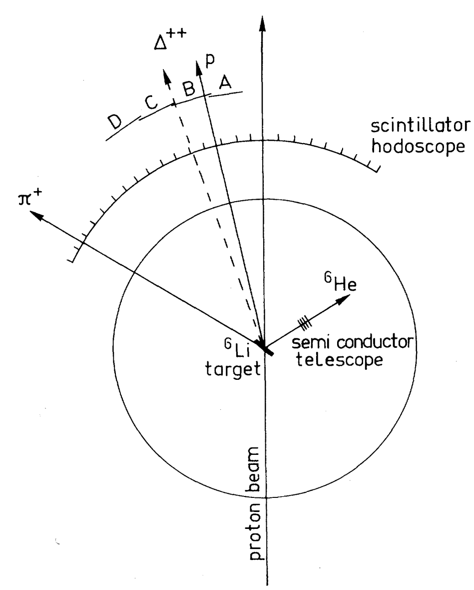

FIG. 1. Experimental setup.

semiconductor telescope in order to detect the Δ^{++} decay products ($p\pi^+$). Information about multiplicity and angle between decay products was thus provided. The hodoscope covered a solid angle of 2 sr and provided a simultaneous measurement of the impacts of the particles. It consisted of a set of 22 scintillators—1.5 m high and 5 cm wide—viewed at each end by photomultipliers. Time signals from the two ends of each element allowed a precision of ± 2.5 cm on the impact localization. Moreover, four plastic scintillators, covering 0.28 sr, were set up in coincidence with the hodoscope in the region of space corresponding to the Δ^{++} decaying protons. The mean geometrical efficiency of such a pattern was about 60% over the intervals $1170 < M < 1290$ MeV and $0.11 < |t| < 0.35$ $(\mathrm{GeV}/c)^2$. The semiconductor telescope, set inside the scattering chamber at 150 mm from the target, was made out of four silicon detectors (30, 375, 700, and 700 μm); one of them (the second one) was a position-sensitive detector giving the angular information: It covered a horizontal aperture of $\pm 5°$ and allowed a determination of the angle better than 0.1°. The beam intensity was low (5×10^8 to 10^9 p/s) in order to avoid pileup in the silicon detectors. The absolute flux of protons was determined by activation measurements of a carbon sample. The ^{6}Li target, laminated under dry argon atmosphere, was 3.2 mg/cm^2 thick. Its isotopic enrichment was 99.7%. The existence of chemical impurities due to target-making procedure will be discussed later. All timing and amplitude signals characterizing an event were recorded on magnetic tape on line with help of a PDP 11/45 computer.

Particle identification is achieved by the standard ΔE-E method. The contamination of the ^{6}He spectrum by alphas is smaller than a few percent. Apart from ^{6}He and $A < 6$ nuclei, one observes some ^{6}Li, ^{7}Li, and ^{7}Be nuclei. These come from fragmentation of the impurity nuclei in the target. Comparison with the data of Greiner *et al.* and Gosset *et al.*[6] allows us to evaluate to about 1% the part of the ^{6}He spectrum due to the fragmentation of impurities. This subtracted background is small but becomes significant at the largest transferred momenta. At high momentum transfer, the signature provided by the hodoscope is necessary and we have considered events with hodoscope multiplicities of 1 (proton only) and 2 (proton and pion). Under these conditions, and after corrections for geometrical and electronic inefficiencies, we obtain the missing-mass spectrum shown in Fig. 2. The resonance is clearly observed up to 0.2 $(\mathrm{GeV}/c)^2$ with a 90-MeV full width at half maximum (FWHM) (slightly smaller than its free FWHM); the three-body continuum

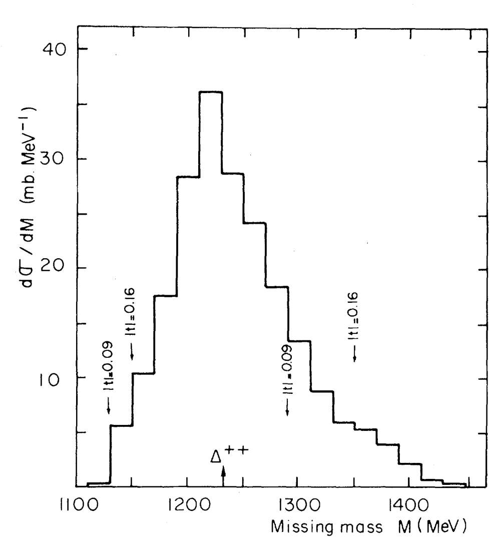

FIG. 2. The ^{6}Li$(p,\Delta^{++})^6$He differential cross section $d\sigma/dM$ vs the missing mass M. The four-momentum transfer interval is 0.09–0.38 $(\mathrm{GeV}/c)^2$. The arrows indicate the experimental cuts for different four-momentum transfers.

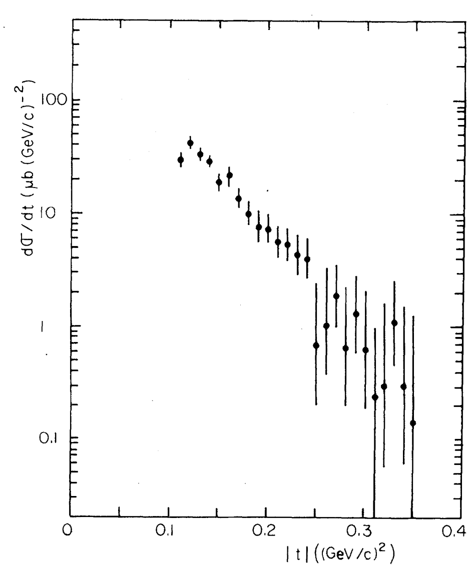

FIG. 3. Differential cross section $d\sigma/dt$ vs $|t|$ for the reaction ^{6}Li$(p,\Delta^{++})^6$He at a proton kinetic energy E_p =1.04 GeV. The integration interval in missing mass is 1170–1290 MeV. A small fragmentation component has been subtracted.

is small in this momentum range. Beyond 0.2 $(\mathrm{GeV}/c)^2$, the statistical significance becomes weaker; the resonance does not show up clearly above the three-body continuum which becomes more difficult to estimate properly. The Δ^{++} production cross section has been extracted by integrating $d^2\sigma/dt\,dM$ over a 1170–1290-MeV interval. It exhibits (see Fig. 3) an exponential decrease from 0.12 to 0.35 $(\mathrm{GeV}/c)^2$ with a slope of 22.6 $(\mathrm{GeV}/c)^{-2}$. A maximum seems to appear at lower values of $|t|$.

Let us try to relate the experimental slope of the cross section for the reaction $p + {}^6\mathrm{Li} \to \Delta^{++} + {}^6\mathrm{He}$ to the elementary production cross section for $pp \to \Delta^{++}n$. We have to disentangle the nuclear structure part from the rescattering corrections, which include the Δ-N interaction.

The reaction is treated in the framework of multiple-scattering theory.[7] If we denote by j the nucleon on which the transition $NN \to \Delta N$ takes place, the total profile function is defined by

$$\Gamma_j(\vec{b}, \vec{s}_1, \ldots, \vec{s}_A, z_j) = \exp(iq_\parallel z_j)\prod_{l=1}^{j-1}[1-\Gamma_1(\vec{b}-\vec{s}_l)]\Gamma_p(\vec{b}-\vec{s}_j) \times \prod_{k=j+1}^{A}[1-\Gamma_2(\vec{b}-\vec{s}_k)],$$

where Γ_1, Γ_p, and Γ_2 stand for the profile functions of $NN \to NN$, $NN \to \Delta N$, and $\Delta N \to \Delta N$, respectively. $\vec{b}$, $q_\parallel$, $\vec{s}_k$, and z_k represent the impact parameter, the longitudinal transfer, and the coordinates of nucleon k in the plane perpendicular to the incident particle axis and along this axis, respectively. By inverting the formula

$$\Gamma_j(\vec{b}) = (2i\pi k)^{-1}\int e^{-i\vec{q}\cdot\vec{b}}F_{fi}(\vec{q})d\vec{q}_\perp,$$

where k is the momentum of the incident particle in the center-of-mass system and $\vec{q}_\perp$ is the transverse transfer, one gets the total amplitude

$$F_{fi}(\vec{q}) = \frac{ik}{2\pi}\sum_{j=1}^{A}\int e^{i\vec{q}\cdot\vec{b}}\langle f|\Gamma_j|i\rangle d\vec{b}.$$

The cross section is then given by $d\sigma/dt = (\pi/k^2) \times\langle|F_{fi}|^2\rangle$ where the mean is obtained by summing over final spin states and averaging over initial spin states.

The amplitudes for the elastic channels are taken to be

$$f_K(\vec{q}) = \frac{(i+\alpha_K)}{4\pi}k_K\sigma_K\exp\left(-\frac{\lambda_K q^2}{2}\right)$$

(subscript K stands for NN or ΔN), where k_K, σ_K, α_K, and λ_K represent the wave number in the center-of-mass system, the total cross section for channel K, the ratio of the real to the imaginary part of the amplitude, and the slope. Spin effects in the rescattering have been neglected in this first calculation.

For the production channel, a somewhat different amplitude has been used in order to take explicitly into account the transition from a proton ($J=\frac{1}{2}$, $I=\frac{1}{2}$) to a delta ($J=\frac{3}{2}$, $I=\frac{3}{2}$). The amplitude takes the form

$$f_p(q) = \frac{i+\alpha_p}{4\pi}G(k_1k_2)^{1/2}\exp\left(-\frac{\lambda_p q^2}{2}\right)\mathcal{P}^\sigma\mathcal{P}^\tau,$$

where $\mathcal{P}^\sigma$ and $\mathcal{P}^\tau$ are spin and isospin operators. The net effect of these operators is to reduce the cross section with respect to the elementary one by a factor $\frac{10}{27}$.

Assuming the wave functions of ${}^6\mathrm{He}$ and ${}^6\mathrm{Li}$ nuclei to be antisymmetrized products of individual particle wave functions, one can calculate the cross section analytically, provided one uses wave functions which can be written as products of a Gaussian $[\exp(-r^2/R^2)]$ and a polynomial (in r^2/R^2). Because the final expression is very lengthy, detailed calculations will be presented in a forthcoming paper.

The values of the parameters α_{NN}, λ_{NN}, and σ_{NN}, after the averaging over spin and isospin, are taken to be -0.27, 0.22 $(\mathrm{GeV}/c)^{-2}$, and 44 mb, respectively.[8] α_p is taken equal to 0 while G is obtained after normalizing to half the experimental $pp \to \Delta^{++}n$ cross section (4.3 mb). We choose $\lambda_p = 0.74$ $(\mathrm{GeV}/c)^{-2}$ which corresponds to the decreasing slope with respect to the transverse four-momentum. The parameter R used to describe the wave function in the harmonic oscillator model is obtained from electron scattering,[9] $(\langle r_{^6\mathrm{Li}}{}^2\rangle - \langle r_p{}^2\rangle)^{1/2} = R\sqrt{\frac{11}{6}}$. This gives $R = 1.78$ fm. The Gartenhaus-Schwartz[10] prescription has been used to account for the center-of-mass correction. The sensitivity to $\sigma_{\Delta N}$ and $\alpha_{\Delta N}$ is illustrated in Fig. 4. In the plane-wave approximation the mean slope is steeper than the experimental one. The value $\sigma_{\Delta N} = 40$ mb gives a value of the cross section at low $|t|$ in agreement with the experimental one. The sensitivity to $\alpha_{\Delta N}$ in this region is low but increases noticeably with increasing $|t|$. A minimum appears, which comes from the interferences between the zero-order term (no rescattering) and the terms including one rescattering, either in the entrance or in the exit channel. Its position depends mainly on the value of $\sigma_{\Delta N}$ and is only slightly shifted when $\alpha_{\Delta N}$ is varied. The importance of the second maximum goes as the value of $\sigma_{\Delta N}$. As a minimum is not

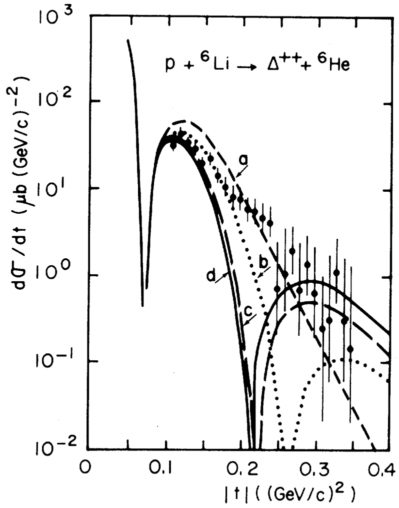

FIG. 4. Differential cross section $d\sigma/dt$ calculated in the Glauber model. The harmonic oscillator parameter is 1.78 fm, and we take $\lambda_p = 0.736$ fm^2. Curve a, plane wave. For curves b, c, and d, $\sigma_{NN} = 44$ mb, $\alpha_{NN} = -0.27$. For curve b, $\sigma_{\Delta N} = 0$, $\alpha_{\Delta N} = 0$; for curve c, $\sigma_{\Delta N} = 40$ mb, $\alpha_{\Delta N} = 0$; for curve d, $\sigma_{\Delta N} = 40$ mb, $\alpha_{\Delta N} = -1$.

observed in the experimental results, it seems more convenient to compare the experimental slope to the mean theoretical slope, defined by a line joining the two maxima. A quantitative agreement occurs for $\sigma_{\Delta N} = 40$ mb and $\alpha_{\Delta N} = -0.7$.

Before drawing more definite conclusions, one has to test the approximations made. Whereas the effect of the Coulomb potential is clearly expected to be small—the Coulomb phase shift never exceeds 0.02—one may question the neglect of correlations between the nucleons as well as spin effects in the rescattering terms, which might produce substantial changes, especially in the minimum region. A better knowledge of the elementary Δ-production amplitude is crucial, as the absolute cross section depends much on its parametrization. In a more fundamental way, one may question[11] the validity of considering the delta as a stable particle as its decay length is comparable to the nuclear diameter.

One may say that the present reaction shows a sensitivity to the parameters of the Δ-N interaction, but extended experimental and theoretical work is needed in order to conclude more precisely. One has to stress that, contrary to the high-energy case, one is very sensitive to nuclear structure.

We wish to thank C. Lazard and R. Lombard for fruitful discussions. We are very much indebted to Y. Bisson and J. Hervieu for their technical help and to the engineers and technicians of the Laboratoire National Saturne for their efficient cooperation. Les Instituts de Physique Nucléaire in Orsay and Villeurbanne are laboratoires associés à l'Institut National de Physique Nucléaire et de Physique des Particules.

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