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CHARACTERISTICS OF THE PRODUCTION OF FAST RESIDUAL NUCLEI IN THE REACTION $Be^9(p, 2Nx\pi)Li^8$

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Some characteristics of the production of fast residual nuclei in the reaction $Be^9(p, 2Nx\pi)Li^8$ are studied. It is shown that up to the amount 750 MeV/c of momentum transferred to the Li^8 nucleus, the experimental data are consistent with the assumption of a quasi-free interaction between the primary nucleon and a proton of the nuclear p shell.

1. INTRODUCTION

MOMENTUM transfer as high as 1100 MeV/c to residual nuclei has been observed when a single nucleon is separated from a light nucleus.[1] It is of decided interest to determine the nature of this effect and its relation to the structure of the target nucleus. It is well known[2-4] that when small amounts of momentum (up to about 200 MeV/c) are transferred to individual nuclei, (p, 2p) and (p, pn) processes can be described using the model of a quasi-free interaction between the incident proton and a nucleon in the appropriate nuclear shell. Computations in [3] pertaining to interactions in the initial and final states show definitely that the given effects can be reduced by using high bombarding energies and light target nuclei. Almost all the presently known experiments with (p, 2p) reactions employed the technique described in [2], whereby the energy state and momentum of the residual nucleus were determined from the combined energy and angular distribution of the two protons. The experimental results obtained in this manner are customarily brought into agreement by using shell wave functions without appreciable "tails" in the high momentum region.

In investigating the characteristics of high-momentum transfer to residual nuclei we aimed to determine their consistency with the aforementioned hypothesis of a quasi-free interaction between the incident and bound nucleons. Be^9 was selected as the target-nucleus because:

1) A sufficiently thin (1.5 mg/cm^2) target could be made of beryllium among the lightest elements.

2) Li^8 residual nuclei can be registered relatively easily in photographic emulsions; a Li^8 track ends in a "hammer track" representing the decay chain

$$Li^8 \xrightarrow[0.8 sec]{\beta-} Be^{8*} \xrightarrow[10^{-16} sec]{} 2\alpha;$$

3) The Li^8 residual nucleus has only two states that are stable against nucleonic decay; these are the ground state and 0.98 MeV.

2. EXPERIMENTAL PROCEDURE

A 1.5 mg/cm^2 beryllium foil was bombarded in a vacuum chamber by a 660-MeV proton beam from the synchrocyclotron of the Laboratory for Nuclear Problems of the Joint Institute for Nuclear Research. Particles formed in the disintegrations of Be^9 passed through a slit system to P9-0 photographic plates bearing a 100-μ emulsion, enabling highly reliable registration of Li^8 nuclei against a large background of lighter particles. Li^8 nuclei were registered at the angles 90° ± 8°, 65° ± 7°, 47° ± 7°, 29° ± 5°, and 20.5° ± 3.5° with respect to the incident proton beam. Continuous evacuation during the irradiation period maintained a chamber vacuum of the order of a few units of 10^{-2} mm Hg, thus eliminating the residual air background.

In order to determine the background of spurious Li^8 tracks (accidental superpositions of α-particles or $Li^{6,7}$ on tracks from disintegrations in the emulsion induced by cascade nucleons) and the Li^8 background arising from the interaction of cascade nucleons with the insensitive surface layer of the emulsion and the chamber walls (there is a 5:1 ratio between the diameter of the collimating cylinder of the chamber and the beam diameter), control bombardments were performed without a target and with $Li^{6,7}$ targets about 0.5 mm thick. Scanning of the control photographic plates revealed practically no spurious or background tracks of Li^8. Special experimental work was done to calibrate the chamber with respect to the relative transmission of each slit, employing the same bombardments as in the main runs, but with polystyrene and gold foils. The transmission was calibrated in thicknesses of Au, controlled by comparing the angular distribution of α particles from a polystyrene target with the corresponding data in [5], where a study was made of C^{12} disintegrations in diamond crystals introduced into an emulsion, using 660-MeV protons. The compared results were found to agree, thus indicating the correctness of the calibration.

The scanners selected only those Li^8 tracks exceeding 5μ in length, where the α particles did not leave the emulsion. Geometric corrections were introduced for the escape of α particles from the emulsion; these corrections took into account the efficiency of Li^8 track registration in the case of different α-particle orientations about the normal to the emulsion. It was found that the dependence of the aforementioned efficiency E on $\cos\beta$, where β is the angle between the α-emission path and the normal to the emulsion surface, can be represented by $E(\cos\beta) = 1 - \cos\beta$. All distributions were plotted so that corrections were applied to the low-momentum, rather than to the high-momentum, portions of the spectra (i.e., all spectra were renormalized identically).

3. EXPERIMENTAL RESULTS

The Li^8 energy spectra were plotted at 20° and 90°, while 50 Li^8 fragments were collected at each of the angles 29°, 47°, and 65° in order to plot the angular distribution. The Li^8 energy distributions are shown in Fig. 1, and the angular distribution in Fig. 2.

As in [1], events involving greater than 1000 MeV/c momentum transfer to the Li^8 nucleus were registered. The following statements can be made regarding the shape of the spectra. Our technique (employing an external target) cannot obviate self-absorption of the low-energy component even with very thin foils. The absence of any reliable range-energy relations for slow Li^8 nuclei in Be prevents us from introducing well justified corrections for Li^8 ranges from 5 to 10μ in the emulsion. It can only be stated that the falling off of the spectra at low energies is associated with this effect alone and with the difficulty of observing very slow Li^8 tracks against a very large background. For Li^8 having ranges $> 10\mu$ the target half-thickness can correspond to energy losses < 1 MeV.

4. DISCUSSION OF EXPERIMENTAL RESULTS

It is interesting to compare our experimental results with the model of a quasi-free interaction between primary nucleons and 1p protons of Be^8 (it should be noted that when a 1s nucleon is ejected the residual nucleus is left so highly excited that it undergoes "cluster-type" decay.)

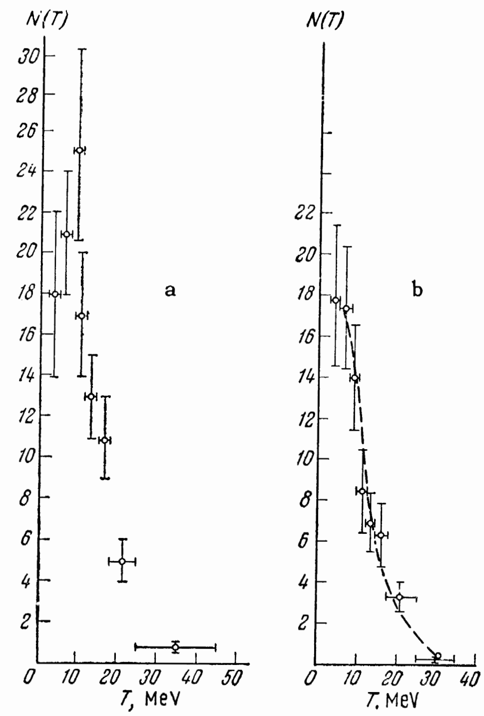

FIG. 1. Li^8 energy distribution at (a) 20° and (b) 90°. The dashed curve was calculated.

The foregoing view can be based theoretically on Shapiro's theory of direct nuclear reactions,[6] which employs the analytic properties of the amplitudes of the appropriate processes. For example, in this theory the considered reaction can be represented by the peripheral diagram in Fig. 3a. However, sufficiently rigorous calculations would require us to know the analytic continuation of the partial amplitudes of p-p interaction, with respect to the nucleonic mass, into the unphysical region for a broad energy range of colliding nucleons. The lack of such data prevents use of the exact theory; at the present time the calculations must be performed using certain rough approximations such as the impulse approximation. When similar experimental data regarding interactions

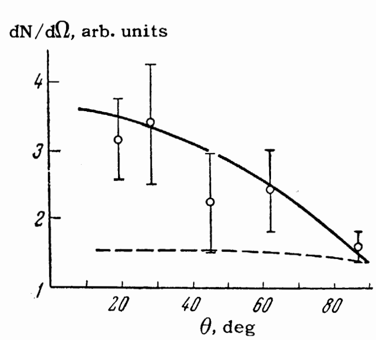

FIG. 2. Li^8 angular distribution. The continuous curve was calculated taking account of meson production, which was neglected for the dashed curve.

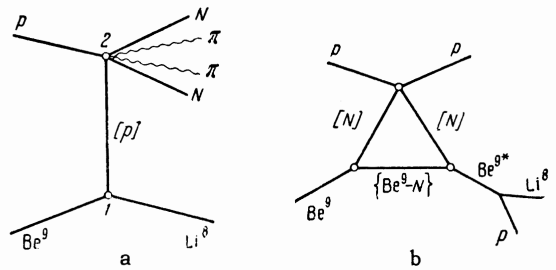

FIG. 3. (a) Peripheral diagram utilized in calculation; (b) one of the possible diagrams representing inelastic proton scattering on Be^9

between fast nucleons and intranuclear nucleons are analyzed by means of the impulse approximation one ordinarily uses the interaction cross sections for free nucleons, neglecting the spin of the intermediate particle; the justification of this procedure is given in [2,7,8], for example. In this case the kinematic characteristics of residual Li^8 nuclei in Fig. 3a are represented by [9]

$$\frac{d^2\sigma}{dT\,d\cos\theta} = \frac{A}{p}\,q\,\frac{K^2(\Delta^2)}{(\Delta^2+m_p{}^2)^2}\,\omega\sqrt{\omega^2-4m_p{}^2}\,\sigma_{pp}^{tot}(\omega), \quad (1)$$

where T, q, and θ are, respectively, the kinetic energy, momentum, and angle of Li^8 relative to the incident proton direction (in the lab. system); p is the incident proton momentum; Δ^2 is the square of 4-momentum transferred at vertex 1 (Fig. 3a); $K^2(\Delta^2)$ is the Be^9 form factor in the "cluster" state $\{Li^8 + p\}$; m_p is the proton mass; ω^2 is the squared total energy of particles produced at vertex 2 in their c.m.s.; σ_{pp}^{tot} is the total cross section for p-p interaction, taken for free protons.

It is clear that all results that can be obtained by means of the foregoing formula will be qualitative and will indicate only the existence or absence of clear disagreements with experiment.

From (1) and the experimental Li^8 energy spectrum at some angle we obtain the function $K^2(\Delta^2)$. The Li^8 energy spectrum at any other angle can then be computed and compared with experiment. Figure 4 shows $K^2(\Delta^2)$ as calculated using the Li^8 energy spectrum at 20°.

The dashed curve in Fig. 1 represents the Li^8 energy distribution at 90°, calculated from (1) by means of the derived function $K^2(\Delta^2)$. The same function was used to compute the Li^8 angular distribution represented in Fig. 2 by the dashed curve, neglecting meson production. The calculated Li^8 energy and angular distributions are seen to represent experiment correctly. It must be emphasized that the derived values of $K^2(\Delta^2)$ pertain to two stable Li^8 states at the same time (0 and 0.98 MeV).

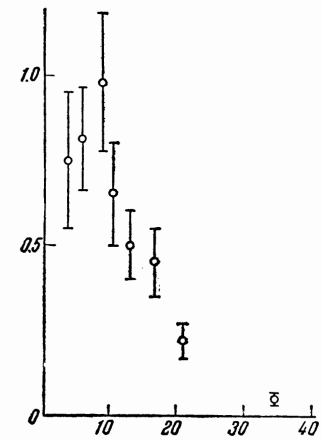

FIG. 4. The function $K^2(\Delta^2)$. The abscissa (in MeV) is $[\Delta^2 + (M_{Be^9} - M_{Li^8})^2]/2M_{Be^9}$.

Our calculations show that for the quasi-free interaction of an incident proton with an intranuclear nucleon large momentum transfer to the Li^8 residual nucleus can be accounted for (at least up to ~ 750 MeV/c). Therefore the very large momenta of residual nuclei in $Be^9(p, 2Nx\pi)$ at E_p = 660 MeV, which were observed in [1] and in the present work, can evidently be treated as effects associated only with a high-momentum "tail" of the momentum distribution of intranuclear nucleons.

In view of the importance of the foregoing conclusion, a more detailed analysis of the given reaction is required, taking into account both the pole diagram and diagrams representing interactions in the initial and final states (for example, various processes of diffractive scattering, and the reabsorption of mesons produced at vertex 2). In the present work we have avoided questions relating to the possibility of inelastic proton scattering on Be^9 (Fig. 3b) with the excitation of a level decaying to a proton and Li^8. This process could be neglected because in the spectrum of Li^8 nuclei moving at an angle of 20° it would be impossible to distinguish groups arising through the practically two-body kinematics of inelastic scattering. We also rejected the allowable, in principle, alternative possibility of large momentum transfer to Li^8—its quasi-elastic ejection from the Be^9 nucleus by an incident proton—in view of the small quasi-elastic scattering cross sections at large angles and the impossibility of accounting for the small difference between the experimental Li^8 energy spectra at 20° and 90° in the given picture.

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