Angular momentum selection rule and the ^{9}Be(π^+, p)^{8}Be reaction at 50 MeV

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Angular distributions have been measured at 50 MeV for the ^{9}Be(π^+, p)^{8}Be reaction leading to the 0^+, 2^+, and 4^+ states of ^{8}Be. An angular momentum selection rule is considered in order to account for the preferential excitation of high spin states. Two-step processes in the framework of the distorted-wave Born approximation and momentum sharing in the two-nucleon model are also discussed.

[NUCLEAR REACTIONS ^{9}Be(π^+,p)^{8}Be, E_π=50 MeV; measured $\sigma(\theta)$; reaction mechanism discussed.]

INTRODUCTION

The high momentum transfer in pion production or absorption reactions should allow the study of high momentum components of nuclear wave functions. Owing to the selectivity observed for high spin states well described by 1p-2h or 2p-1h configurations, we may consider the (π^+,p) or (p, π^+) reactions in two different ways: either to use it as a spectroscopic tool or to trace out the reaction mechanism with the aid of states of well-known structure. Despite the great variety of experimental data, we still ignore the exact mechanism of these reactions. Experiments which have been performed in order to disentangle nuclear structure and mechanism are the study of the cross-section variation with respect to the incident energy at fixed momentum transfer,[1] the production or absorption of negative pions[2] and the production by polarized protons.[3] Although there does not yet exist a comprehensive analysis of the available data, there is no doubt that most of the levels excited in (π^+,p) or (p, π^+) reactions cannot be explained in the frame of the simple pickup or stripping models. A good illustration is found in our previous experiment on ^{16}O.[4] The high ratio observed between the population of the $(p\frac{3}{2})^{-1}$ and $(p\frac{1}{2})^{-1}$ hole states of ^{15}O could not be explained only by nuclear structure considerations. A simple pickup model predicts only a factor of about 2 as observed in other neutron pickup reactions.[5,6] To account for the preferential excitation of high spin states it is tempting to consider a selection rule, used so far for heavy ion transfer reactions,[7] that one can formulate as follows: if one assumes that the reaction takes place at the surface of the nucleus, one has to consider the classical angular momentum transfer $\Delta l = |\vec{k}_p - \vec{k}_\pi| R$, which is of the order of 6 at 50 MeV for an $A=10$ target. For the reaction to occur, this angular momentum Δl must be matched to $\Delta L = |\vec{J}_A - \vec{\frac{1}{2}} - \vec{J}_B|$, which represents the quantum angular momentum transfer. High spin values of the initial (A) and final (B) nuclei are those which provide the best matching conditions $\Delta l = \Delta L$. The applicability of such an angular momentum mismatch rule to a (π^+,p) reaction implies that, at our energies, these reactions take place preferentially at the surface of the nucleus.

In the case of pions however, such a rule seems *a priori* paradoxical at this energy because the mean free path of a pion $\lambda = 1/\sigma\rho = 5$ fm is of the order of the dimension of the nucleus.

The ^{9}Be(π^+,p)^{8}Be reaction has been chosen as a test of this selection rule. The ^{9}Be nucleus is particularly adapted since the reaction involves the 4^+ state of ^{8}Be which meets the best matching conditions $\Delta l = \Delta L = 6$. In addition, the comparison of the relative excitation of the 0^+, 2^+, and 4^+ rotational sequence states should help us to clarify the reaction mechanism.

EXPERIMENTAL METHOD

The experiment was performed on a pion channel of the 600 MeV Saclay Electron Linear Accelerator. The 55 MeV pion beam, corresponding to 50 MeV at the target center, had a 3×10^5 π^+/s intensity. The 98% purity ^{9}Be target was 2.067 g cm^{-2} thick and was set so as to obtain the best energy resolution. The 160 MeV protons were detected in a range telescope (Fig. 1) consisting of thirteen plastic scintillators of increasing size to minimize the loss of protons by multiple scattering associated with the carbon absorber. All 2 mm cells, corresponding each to 1.3 MeV in excitation energy, allowed us to cover a 14 MeV range per measurement. Several overlapping measurements were recorded in order to obtain a complete energy spectrum for each angle. The sequential decay of scattered pions in flight or at rest (in

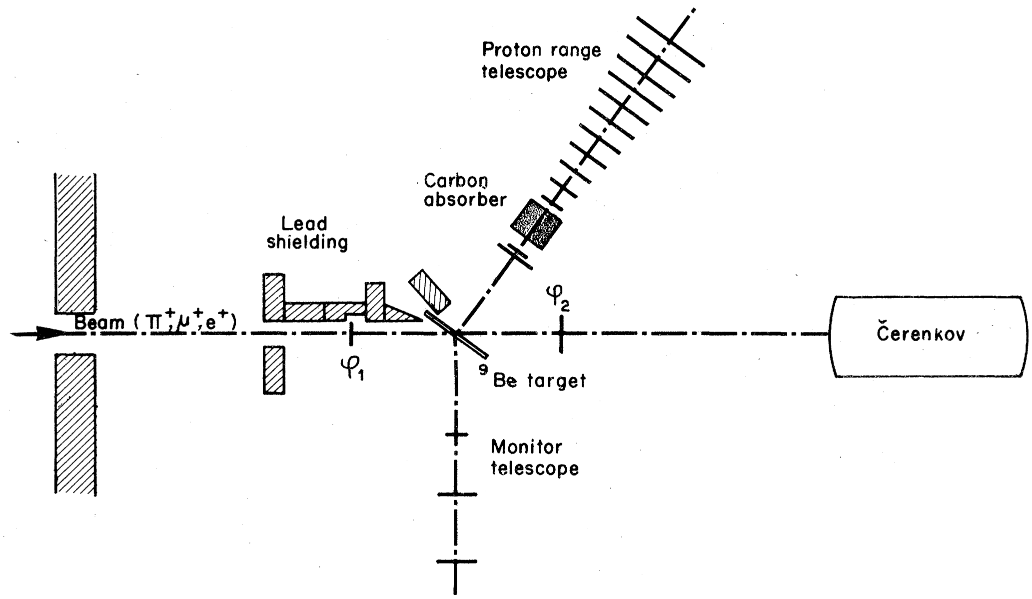

FIG. 1. Experimental setup.

the carbon absorber) $\pi^+ \to \mu^+ + \nu_\mu$ and $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$ is a possible contamination background. Proton selection was made by setting the thresholds on the first three scintillators so as to reject the background due to scattered pions and muons arising from these pions. Each signal of the last eleven scintillators was sent to a pattern unit triggered by the coincidence of the first three scintillators. The rejection efficiency of parasite particles was first estimated using a Monte Carlo method and then checked experimentally in the elastic scattering of pions on protons. Electron contamination from decaying muons stopped in the carbon absorber was ruled out because of the large decay time of the muon (2.2 μs). The incident pion beam intensity was monitored with a three-scintillator telescope set at 90°, calibrated at low intensity with respect to the in-beam counters φ_1 and φ_2. Beam electron contamination was eliminated by the use of a Čerenkov counter in anticoincidence. The effective beam muon contamination was estimated at about 15%.

The importance of the lead shielding is demonstrated by the following facts: 12% of the incoming pion beam turns into muons; this considerable muon flux (~3.5×10^4 μ^+/s) as compared to the proton flux (~0.2 p/s) is emitted in a cone of 17° and the wide angular acceptance of our telescope, ±4°, prevents the measurement of angles lower than 25°. In addition, at 30° and 40° a possible contamination by the (π^+,p) reaction on lead is eliminated by a shielding located after the target.

The absolute energy calibration of the range telescope was made by measuring the reaction ^{12}C$(\pi^+,p)^{11}$C at 50 MeV for which the ground state of ^{11}C is predominantly excited. The $\frac{3}{2}^-$ state cross section has been estimated to be about 30 μb/sr. This value corresponds to Amato's results,[8] but is lower than the value of Amann[9] by a factor of 2. A precision better than ±0.3 MeV was then achieved.

The range straggling parameter in C and CH, the angular aperture of the beam, the angular acceptance of the telescope, the momentum dispersion of the beam, and the contribution of one cell contribute to the resolution by 0.98, 0.13, 0.1, 1.03, and 0.38 MeV, respectively, resulting in an E^* resolution of 4.7 MeV [full width at half maximum (FWHM)]. In order to extract values of the cross sections, proton spectra were decomposed using a χ^2 minimizing program. The fitting function $f(E^*)$ was first chosen to be a sum of Gaussians with the experimental resolution and of the convoluted three-body continua. As indicated on Fig. 2, the three-body continua considered were $(\pi^+,p\alpha)$ $E_s=-0.09$ MeV, $(\pi^+,2p)$ $E_s=17.26$ MeV, and (π^+,pn) $E_s=18.90$ MeV. In fact, due to the large natural width of the 2^+ level at 2.94 MeV and of the 4^+ level at 11.4 MeV, Gaussians proved to be inadequate. The function obtained by convolution of Lorentzians of 1.56 MeV (2^+) and 3.5 MeV (4^+) width[10] with the Gaussian resolution curve was employed. In addition to these states, 4 Gaussians were used for the higher levels.

Figure 2 shows such a decomposition for the energy spectrum summed over all angles. One

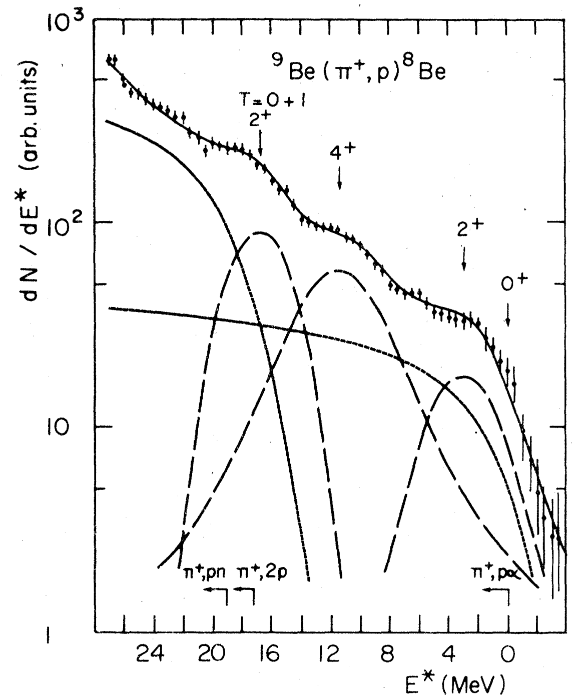

FIG. 2. Excitation energy spectrum summed over all angles. The dashed lines indicate the contributions of the 2^+, 4^+, and 2^+ ($T=0+1$) levels. The dotted curves represent the three-body continua. The fit (sum of all contributions) is indicated by the solid line. For the sake of clarity the contributions of other levels are omitted.

could argue that the long range tail of the Lorentzian curve is responsible for the very low cross section of the ground state and of a substantial decrease of the 2^+ state. Nevertheless, it has been shown that functions decreasing more sharply, such as Gaussians, give bad fits in the intermediate region (~6 MeV). Errors in the extraction of the number of protons for each level reflect the statistical uncertainties as well as the choice of the fitting function $f\ (E^*)$.

Some corrections have been made to the data. The loss of protons through nuclear reactions in the carbon absorber and the scintillators amounts to 20%.[11] Variations of the solid angle with the precise location of the impact on the target have been calculated: the average solid angle is 20 msr. Pion decay between the upstream monitor and the target is 3.4%. All these factors give an overall renormalization of the cross section of 1.22. An uncertainty of ±10% in the absolute normalization is due primarily to the monitor calibration and to pion decay along the beam transport line.

EXPERIMENTAL RESULTS AND DISCUSSION

The angular distributions of the protons leading to the 0^+, 2^+, and 4^+ states of ^{8}Be are presented on Table I and Fig. 3. These results are in agreement with the integrated cross section over angle and excitation energy given by Amato.[8]

The first characteristic trend is the excitation of the 4^+ state and its importance, as predicted by the selection rule. Indeed, in a simple pickup model, this state cannot be reached by a p-shell neutron removal from the ground state of ^{9}Be. This state is also observed in ordinary pickup reactions at large momentum transfer.[5] Its rather smooth angular distribution—the overall variation over the angular range is only 3.5—and its predominance over the 0^+ and 2^+ states indicate that it corresponds to an f-shell pickup or a multistep process.

With a 6% f-shell admixture[12] in the ^{9}Be ground state, we expect the $f\frac{7}{2}$ neutron removal to give an important contribution.[13] Two-step processes involving inelastic excitation in the entrance channel are supported by the large deformation parameter of the $K=\frac{3}{2}$ rotational band.[14] Transitions through states of this band ($\frac{5}{2}^-$ or $\frac{7}{2}^-$) allow the $p\frac{3}{2}$ neutron transfer, while the very low transition rate to the ^{8}Be ground state substantially reduces the inelastic coupling in the outgoing channel.

The strong similarity of the 2^+ angular distribution with the $\frac{3}{2}^-$ angular distribution for the ^{15}O nucleus[4] suggests that this transition proceeds mainly through the normal $p\frac{3}{2}$ neutron transfer from the ground state of ^{9}Be.

The 0^+ state is weakly excited, as expected from the selection rule ($\Delta L=2$). The discrepancy with the $p\frac{3}{2}$ neutron removal cross section in carbon or oxygen (of the order of 30 μb/sr at 30°) is difficult to understand in the simple pickup model, considering that the spectroscopic factor for the 0^+ state is 0.58.[15] Such an effect has already been observed in the (p,d) reaction at 155 MeV (Ref. 5), where the cross section of the 0^+ state is three times smaller than predicted.

If we now consider the ratios of excitation of the three states in ^{8}Be, it is interesting to compare these with the ratios obtained in other neutron

TABLE I. Differential cross sections of the ^{9}Be(π^+, p)^{8}Be reaction at 50 MeV in the laboratory system.

θ_{lab} (deg)	$(d\sigma/d\Omega)$ (0^+) (μb sr^{-1})	$(d\sigma/d\Omega)$ (2^+) (μb sr^{-1})	$(d\sigma/d\Omega)$ (4^+) (μb sr^{-1})
30	≤1.11	8.12 ± 1.00	27.5 ± 2.1
40	≤0.52	4.13 ± 0.73	13.9 ± 1.6
75	≤0.26	0.84 ± 0.33	7.9 ± 1.9
100	≤0.32	1.07 ± 1.00	9.2 ± 2.9
120	≤0.48	1.85 ± 1.00	14.2 ± 2.6

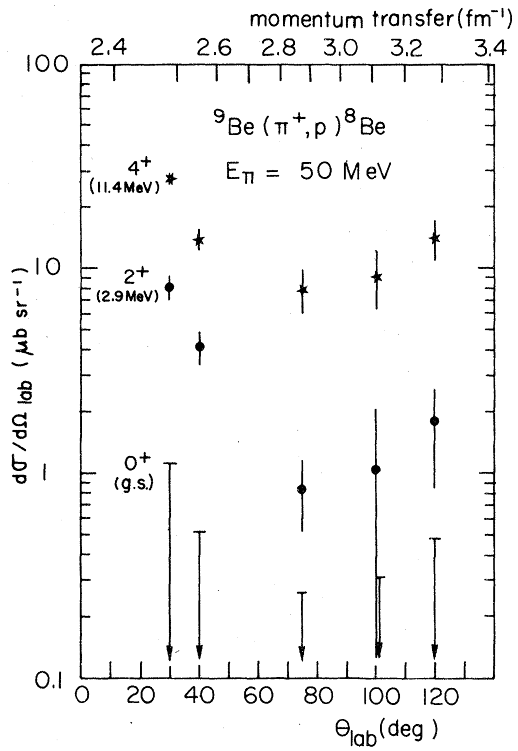

FIG. 3. Angular distributions corresponding to the 0^+, 2^+, and 4^+ states of ^{8}Be.

pickup reactions at the same momentum transfer, in order to get rid of the nuclear structure factors Extrapolation of the results of the (p,d) reaction at 155 MeV (Ref. 5) gives the ratios 5 : 2.5 : 1 for the $4^+ : 2^+ : 0^+$ states. In pion absorption, we observe the same trend but the ratios are 27 : 8 :1 at 30°. The ratio $4^+ : 2^+$, which varies with momentum transfer, presents a rapid increase (up to 10 at the minimum of the angular distribution) followed by a slow decrease at backward angles. For the $2^+ : 0^+$ ratio, the situation is not so clear as we have only upper limits. A more dramatic example was found in the $^{16}O(\pi^+,p)^{15}O$ reaction[4] where the ratio $\frac{3}{2}^- : \frac{1}{2}^-$ is about 10 : 1, whereas a ratio 3 : 1 is observed in the (τ, α) reaction[6] at the same momentum transfer (2.5 fm^{-1}). The similarity observed between (π^+,p) (Ref. 9) and (p,d) (Ref. 16) on ^{12}C does not apply to our results on ^{9}Be and ^{16}O. In fact, this similarity does not hold with increasing momentum transfer: one observes that the differences between the angular distributions for different states become more pronounced in (π^+,p) than in (p,d) reactions. This effect can be explained by the fact that the nuclear wave function is not probed in the same momentum region because of differences in distortions.

Following the suggestion of Wilkin,[17] it would be interesting to compare our angular distributions with not yet existing (p,d) data at 400 MeV. Such a comparison would serve as a test of the triangle-graph mechanism discussed by Wilkin. However, the comparison would only hold within a factor of 2, as we are at the edge of the 3-3 resonance.

Besides the observation of the rotational sequence in ^{8}Be, one notes an important excitation of the isospin-mixed doublet of 2^+ states at 16.6 and 16.9 MeV. Its cross section is difficult to extract because of the three-body continua $(\pi^+, 2p)$ and (π^+, pn) and of the presence of other higher levels, but it is comparable in magnitude to the cross section of the 4^+ level. Other evidence for $T_>$ levels in carbon[9] and oxygen[4] has been seen.

The preferential excitation of high spin states observed in the (π^+,p) reaction on ^{9}Be and ^{16}O is qualitatively explained by the mismatch selection rule. Such a rule is not in contradiction either with two-step processes[18] or with momentum sharing.[19,20] Two-step processes proceed through target high spin intermediate states. These states favor the angular momentum transfer because they are associated with the excitation of one or more nucleons above the Fermi sea. The momentum sharing involved in a two-nucleon mechanism is realized through the excitation of nucleons to higher shells. In contradistinction to the selection rule, these other mechanisms do not assume a surface localization of the reaction. Nevertheless, as we are dealing with low excitation energy levels in the residual nucleus ^{8}Be (or ^{15}O), only $1p$ nucleons are concerned. Since one knows that pion absorption takes place predominantly on two correlated nucleons, we may say that the reaction occurs more likely in the region where the probability of finding two close nucleons is maximum. This maximum of the probability distribution for p-shell nucleons appears at 2.3 fm, which is not so far from the value of the nuclear radius (2, 6 fm) of ^{9}Be.

The study of a single reaction, such as the (π^+,p) reaction, at a single incident energy is, however, not enough to disentangle the various competing reaction mechanisms.

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