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Influence of Nuclear Cluster Structure in Proton-Induced Pre-Equilibrium Composite Particle Emission

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Abstract. Recent statistical multistep analyses of the pre-equilibrium reaction ^{93}Nb(p,α) at incident energies of 65 and 100 MeV are reviewed. It is shown that the α-cluster structure of the target nucleus is prominently displayed at the lower incident energy, whereas at the higher value its presence is obscured by the dominance of three-nucleon pickup. This result appears to be simply associated with a difference in the details of the effective momentum mismatch experienced by a cluster knockout mechanism, as opposed to a pickup process.

1. Introduction

It has been known for many years that the mechanism of pre-equilibrium (p,α) reactions reveals itself as closely related to a basic statistical multistep process. Cross section and analyzing power angular distributions over the complete range of possible emission energies on various target nuclei are described successfully, for example, by the quantum mechanical theory of Feshbach, Kerman and Koonin (FKK)[1]. The multistep character of the pre-equilibrium reaction is reflected in large excursions in the analyzing power values at high emission energy. Towards lower emission energies, however, the analyzing power angular distributions become featureless as the successive multisteps effectively wash out the polarization transferred by the projectile to the nuclear system. In addition, the shapes of analyzing power angular distributions are especially sensitive to competition between cluster knockout and three-nucleon pickup as part of the statistical multistep chain. In this way Bonetti *et al.* [2] found that the ^{58}Ni(p,α) reaction at an incident energy of 72 MeV displays the features associated with cluster knockout exclusively. This result was recently confirmed for ^{93}Nb(p,α) at a close incident energy of 65 MeV [3, 4]. Thus preformed clusters in ^{58}Ni and ^{93}Nb are implicated as clearly influencing the shapes of the analyzing power angular distributions at incident energies around 70 MeV. Very surprisingly, on ^{93}Nb, but at an incident energy of 100 MeV, three-nucleon pickup clearly dominates [4]. An explanation of this unusual incident-energy dependence is offered in Ref. [4] as resulting from the basic momentum mismatch between the incident and exit channels in a (p,α) reaction. The purpose of this paper is to review the evidence presented in Ref. [4, 5], and to draw conclusions regarding the possible trend expected for the target dependence of the observed phenomenon.

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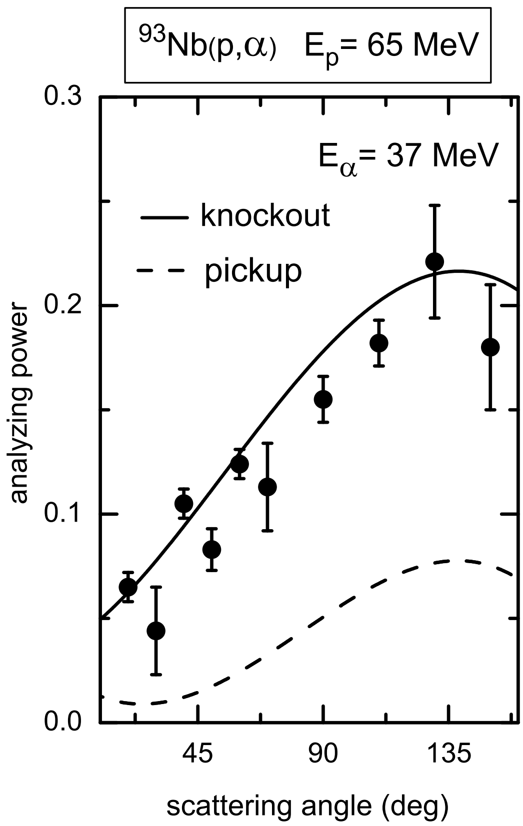

Figure 1. Analyzing power angular distribution for the ^{93}Nb(p,α) reaction at an incident energy of 65 MeV and an α-particle emission energy of 37 MeV. The solid curve is a calculation based on α-cluster knockout as the terminating reaction in the statistical multistep chain, whereas the dashed curve is for three-nucleon pickup leading to α-particle emission. The figure is adapted from one published in Ref. [4].

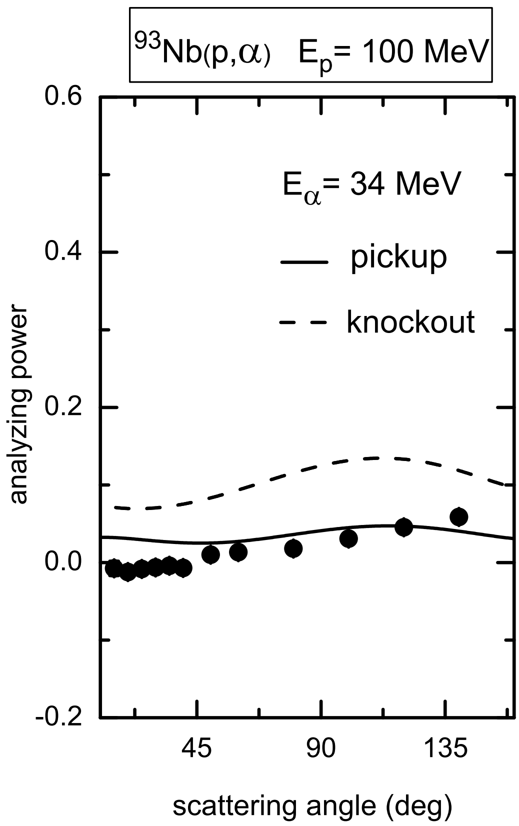

Figure 2. Analyzing power angular distribution for the ^{93}Nb(p,α) reaction at an incident energy of 100 MeV and an α-particle emission energy of 34 MeV. The meaning of the theoretical curves are switched from those in Fig. 1 to emphasize that in this figure the calculation in which pickup is the terminating step agrees with the experimental values. The figure is adapted from one published in Ref. [4].

2. Incident-energy trend of competition between cluster knockout and pickup in the reaction ^{93}Nb(p,α)

Theoretical FKK predictions [4] for either cluster knockout or three-nucleon pickup as the final step in the statistical multistep chain are compared in Fig. 1 with measured [6] analyzing power angular distributions for the reaction ^{93}Nb(p,α) at an incident energy of 65 MeV. Although the shapes of the theoretical angular distributions are qualitatively similar, the absolute magnitudes differ by more than a factor of two, which is a significant difference. This demonstrates the dominance of an α-cluster mechanism in the reaction process. Similar calculations for ^{93}Nb(p,α) are displayed in Fig. 2 for an incident energy of 100 MeV. However, at this higher incident energy we find that the comparison between the theoretical results and the experimental analyzing power distribution favours pickup. Note that in both figures preferred theoretical results are consistently indicated by solid curves, which means that the convention for Fig. 1 is different from that of Fig. 2, as indicated.

Clearly the identity of the dominant reaction mechanism for ^{93}Nb(p,α) at an incident energy of 65 MeV is consistent with that found previously for ^{58}Ni(p,α) reaction at an incident energy of 72 MeV. It now needs to be understood why at 70 MeV the (p,α) reaction displays properties normally associated with α clustering in the target nucleus, whereas at 100 MeV it is insensitive to the cluster structure. This is discussed in Refs. [4, 5]. Use is made of the fact that in distorted-wave Born approximation (DWBA), which is an important ingredient of the FKK formulation (see for example Ref. [7]), the cross section is related to radial integrals which in turn are roughly a function [5] of the overall momentum mismatch q. This quantity is defined as [4]:

$$q = q_{\rm out} - \frac{\Delta L}{R} - q_{\rm in} \, , \tag{1}$$

where $q_{\rm in}$ and $q_{\rm out}$ are the linear momenta in the incident- and exit channels, respectively, ΔL is the angular momentum transfer and R is the nuclear radius associated with either an α-cluster knockout or a three-nucleon pickup system relative to the core part of the target nucleus. As formulated Eq. 1 applies to small scattering angles. As discussed in Refs. [4, 5] α-cluster knockout is expected to be associated with a low (or even zero) angular momentum transfer, whereas in pickup fairly large transfers may occur. Roughly gaussian shapes are assumed for the momentum dependencies of the wave functions of both an α-cluster and a three-nucleon system. The large momentum difference in knockout restricts the cross section to roughly the exponentially-falling part of the wave function. The cross section for pickup, on the other hand, is favoured by the contribution of angular momentum transfer which maximizes it. This gives an incident-energy dependence of the pickup cross section which is centred around $q = 0$ for $\Delta L = 8$.

Results of explicit DWBA calculations are presented in Ref. [4], of which Fig. 3 is an adapted version. Cross sections associated with either pickup or cluster knockout have been extracted from the experimental results as described in Ref. [4], and theoretical calculations are normalized to the extracted cross section values. The dominant reaction mechanism for ^{93}Nb(p,α) as a function of incident energy, as then reflected in the corresponding analyzing power angular distribution, is simply determined by the process which has the largest cross section at a given incident-energy value. In Fig. 3 dashed arrows compare relative cross section magnitudes at incident energies of 65 and 100 MeV for the two reaction mechanisms. For knockout the cross section is substantially larger at an incident energy of 65 MeV than the corresponding contribution from pickup. At an incident energy of 100 MeV the situation is reversed.

Apart from the kinematic influence of momentum mismatch as discussed above, the absolute cross sections associated with knockout or pickup processes are also determined by either cluster spectroscopic factors or three-nucleon amplitudes, respectively. This fact implies that the target structure also influences the extent of the observed competition between the two mechanisms.

3. Summary and conclusion

Results for the pre-equilibrium ^{93}Nb(p,α) reaction at incident energies of 65 and 100 MeV have been discussed in terms of the signature of an α-cluster structure of the target nucleus. It was explained how cluster knockout and three-nucleon pickup compete to determine the characteristic shape of the analyzing power angular distribution by means of which the dominant reaction is identified. The proposed explanation of the apparent change in the mechanism with a relatively small increase in the incident energy from 65 MeV to 100 MeV appears to be confirmed with explicit DWBA calculations. Clearly the target dependence of the phenomenon should be explored in future work.

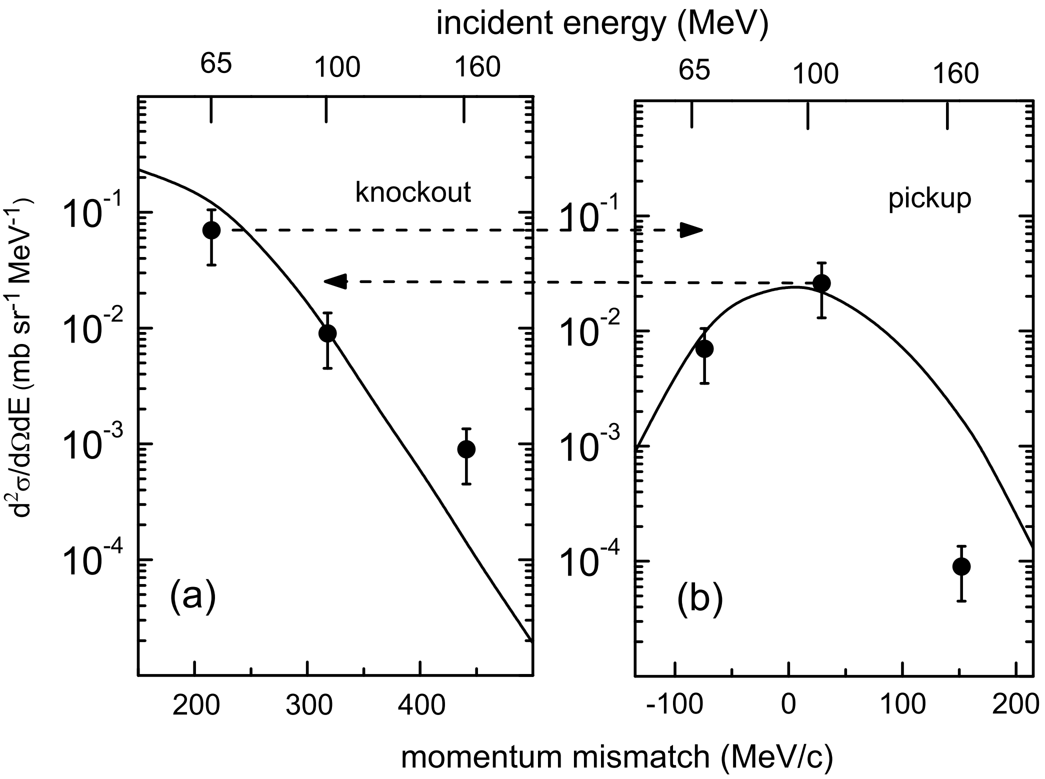

Figure 3. Double-differential cross section for the ^{93}Nb(p,α) reaction corresponding to yields from a knockout mechanism (a) and pickup (b). Results at emission energies 20 MeV lower than the incident energies are shown as a function of overall momentum difference (scales on the lower horizontal axes) and the incident energy is indicated on the top horizontal axes. The curves are DWBA predictions. The figure is adapted from one shown in Ref. [4].

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