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ONE- AND MULTI-STEP PROCESSES IN THE ^{144}Nd(^{12}C,^{14}C) REACTIONS*

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Abstract:

Two very different types of angular distributions, one having a normal bell shape and the other being much more constant with angle were observed in the ^{144}Nd(^{12}C,^{14}C) reaction, for two well known 2^+ states of ^{142}Nd. The fits to these angular distributions by DWBA and/or CCBA confirms the conclusion that the data give definite evidence for the importance of multi-step processes. A comparison with the ^{144}Nd(p,t) reaction is also discussed.

In previous work[1,2] on the ^{144}Nd(p,t)^{142}Nd reaction, the excitation of the ground (0_g^+) state, the first excited (2_1^+) state, the 2.98 MeV (0_2^+) state and the 3.49 MeV (2_2^+) state in ^{142}Nd (N=82) was investigated. The purpose of the present work is to study these and additional states via the ^{144}Nd(^{12}C,^{14}C) ^{142}Nd reaction. Our interests are to learn to what extent the light-ion and heavy-ion induced two-neutron pickup reactions are similar and to determine the effects of multi-step processes in heavy-ion transfer reactions.

The most remarkable feature found in the previous (p,t) work[1,2] was that the transitions to the 0_g^+, 0_2^+ and 2_2^+ final states were strong and were of one-step nature, while the transition to the 2_1^+ state was much weaker and also had an anomalous angular distribution markedly different from what was expected for a one-step L = 2 transition. The difference in the behavior of the 2_1^+ and 2_2^+ transitions was attributed to the following distinct properties of those states.[2] The 2_2^+ state is a collective state of two particle, two hole nature in the N = 82 closed shell, i.e., a superposition of monopole and quadrupole pairing vibrations.[3] Therefore, it can be excited strongly by a direct L = 2 type 2-neutron pick-up reaction. On the other hand, the 2_1^+ state consists dominantly of a proton particle-hole quadrupole vibrational configuration; thus a direct 2 neutron transfer process is substantially inhibited and higher order processes may contribute significantly. Indeed, the anomalous behavior of the 2_1^+ cross section, which defied explanation in terms of DWBA calculations, was well accounted for by coupled-channel Born approximation (CCBA) calculations, which took into account the effect of inelastic scattering.[2]

The ^{144}Nd(^{12}C,^{14}C) experiment was performed using a 78-MeV ^{12}C beam from the Berkeley 88-inch cyclotron. Reaction products were detected in the focal plane of a magnetic spectrometer.[4] Particle identification and energies of the reaction products were obtained by a combination of magnetic rigidity, dE/dx, total energy and time-of-flight. Figure 1 shows an energy spectrum of the ^{14}C ions. A 300 μg/cm^2 self-supporting isotopically-pure metallic ^{144}Nd target gave a resolution of 260 keV. Angular distributions of the ^{14}C groups leading to 0_g^+, 2_1^+, 0_2^+, 2_2^+ states and a group at about 2.08 MeV consisting of 3_1^-, 4_1^+, 0_1^+ were measured from θ_{lab} = 8° to 55° in 2.5° steps.

Figure 2 gives the measured differential cross sections of the five ^{142}Nd groups, and one may conclude that the data have the following properties: (i) The 0^+_g, 0^+_2 and 2^+_2 states are excited strongly and have bell-shaped angular distributions which are characteristic of one-step transitions, with peaks appearing at $\theta_{cm} \approx 45°$; (ii) the 2^+_1 transition is strongly inhibited and has a quite anomalous (flattened) angular distribution; (iii) below the excitation energy of 3.5 MeV, 0^+_g, 0^+_2 and 2^+_2 are the only states that are excited strongly, in spite of the fact that there are about 25 states in this energy range known from other experiments.[5] All these features are very much reminiscent of the situation for the (p,t) reaction.[1,2]

Since the elastic scattering of ^{12}C by ^{142}Nd was not available, we began our analysis by using the Argonne potential,[6] which has V = 100 MeV, W = 25 MeV, r_0 = 1.22 fm and a = 0.50 fm, and searched on radius and diffuseness so as to give the best over-all fit to our transfer data. The resulting potential, (r_0 = 1.18, a = 0.55 fm) was used in all theoretical calculations. The elastic cross section predictions did not change much from that obtained with the unaltered Argonne parameters, nor differ very much from that obtained by using the parameters of Becchetti et al.[7]. We may therefore say that the conclusion we derive below is rather insensitive to the choice among optical potential parameters which are currently accepted.

In constructing the form factor(s) to be used in the DWBA and/or CCBA calculations[8,9], the wave functions of ^{142}Nd and ^{144}Nd were constructed in exactly the same manner as they were in Refs. 2 and[10]. The overlap of these two wave functions gives the wave function of the two extra neutrons in ^{144}Nd. A corresponding wave function for the two extra neutrons in ^{14}C can be obtained by using the results of Cohen and Kurath[11] and after transforming each of these two-neutron wave functions into the center-of-mass (cm) and relative parts, only the term that involved the relative motion which had no node and ^1S coupling was retained. The radial part of the corresponding cm part was then smoothly connected to the appropriate tail that corresponded to a Woods-Saxon potential with a radius parameter $r_0 = 1.2$ fm and a diffuseness $a = 0.65$ fm.

The cross section for the 0_g^+ and 2_1^+ final states were obtained by performing exact finite-range (EFR)-CCBA calculations, in which $0^+ - 2^+$ Nd states were coupled in both incident and final channels, with $\beta_2 = 0.125$ and 0.096 for ^{144}Nd and ^{142}Nd, respectively. As is seen in Fig. 2 good simultaneous fits to both bell-shaped 0_g^+ and flattened 2_1^+ angular distributions are obtained. A corresponding EFR-DWBA cross section is also given by a dotted line for the 2_1^+ state, which is seen to have a completely different shape from the experimental angular distribution. The DWBA 0_g^+ cross section, which is also given by a dotted line, will be discussed later.

It is worth emphasizing that not only the angular distribution, but also the relative magnitude of the EFR-CCBA 0_g^+ and 2_1^+ cross sections were obtained correctly. It is worth noting further that the CCBA 2_1^+ cross section (solid line) was obtained as a result of destructive interference between the one-step DWBA process and the two two-step processes; 0_g^+ (^{144}Nd) → 0_g^+(^{142}Nd)→ 2_1^+ (^{142}Nd) and 0_g^+ (^{144}Nd) → 2_1^+ (^{144}Nd) → 2_1^+ (^{142}Nd). The 2_1^+ cross section given by a broken line was obtained by considering <u>only</u> these two-step processes. The very anomalous angular distribution results from this interference. Such a result is rather similar to what was experienced in the corresponding (p,t) work, where the contributions of the two two-step and the one-step processes were comparable to one another and their strong interference made the 2_1^+ angular distribution also anomalous.[2]

A similar EFR-CCBA calculation was made considering a $0_g^+ - 3_1^-$ coupling in ^{142}Nd, and the resultant 3_1^- cross section, shown in Fig. 2, agrees rather well with the experimental angular distribution to the group at 2.08 MeV. The predicted magnitude obtained with $\beta_3 = 0.106$, is, however, too small by a factor of N = 2.7. Since the experiment includes the 3_1^-, 4_1^+ and 0_1^+, cross sections, however, we do not attach much significance to this comparison.

The calculation of the 0_2^+ and 2_2^+ cross sections was made in terms of EFR-DWBA, assuming that the excitation takes place only via pairing vibrational components in these states which have monopole and quadrupole nature, respectively.[12] As is expected the resultant cross sections (Fig. 2) are basically bell shaped, and agree satisfactorily with experimental angular distributions. The relative normalization factors N = 0.92 and N = 0.85, respectively, for these two states are sufficiently close to unity, indicating that the wave functions we used to describe these two states are basically correct.

It should be finally noted that, both experimentally and theoretically, the peak of the bell-shaped angular distribution for the 0_2^+ state appears at 45°. On the other hand the experimental peak for the 0_g^+ state appears at 43°, i.e. a shift by 2° to forward angle takes place and our CCBA calculations explain this. The corresponding DWBA cross section, however, has the peak at 45° (in agreement with that for the 0_2^+ state) and the angular distribution (dotted line) fits the experiment rather poorly. The origin of the shift of 2° of the peak position in going from DWBA to CCBA is the destructive interference in the latter between the two-step 0_g^+ (^{144}Nd) $\rightarrow$ 2_1^+ (^{144}Nd) $\rightarrow$ 0_g^+ (^{142}Nd) amplitude and the one-step 0_g^+ (^{144}Nd) $\rightarrow$ 0_g^+ (^{142}Nd) amplitude. This destructive interference is stronger (weaker) for partial waves whose orbital angular momentum ℓ is smaller (larger) than the grazing angular momentum ℓ_g. Thus, the effective value of ℓ_g for CCBA is larger than that for DWBA which results in the shift of the peak position to a smaller angle.

In summary, (i) the mechanism of the ^{144}Nd(^{12}C,^{14}C) reaction is quite analoguous to that of the ^{144}Nd(p,t) reaction; (ii) the comparison of the transitions to the two types of 2^+ states gives a definite evidence for the importance of two-step processes[9,13]; (iii) since the direct transfer signature for this system is a clear bell-shaped angular distribution, the anomalous nature of the 2_1^+ excitation is much more conspicuous than that observed in the (p,t) case[1,2]. (iv) The coupling effect can be significant in predicting the correct angular distribution, in particular the peak position, even when the angular distribution has a simple bell shape. This was exemplified in our 0_g^+ cross section.

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FIGURE CAPTIONS

Fig. 1. Energy spectrum of the ^{144}Nd(^{12}C,^{14}C) reaction. Excitation energies in ^{142}Nd are shown in parentheses in MeV. The peak corresponding to the first excited state in ^{14}C is also shown.

Fig. 2. Experimental and theoretical angular distributions of the ^{144}Nd (^{12}C,^{14}C) reaction at E_{lab} = 78 MeV. Each curve is labeled with a normalization factor N, so chosen that N = 1 for the 0_g^+ state. (Without this renormalization, all the theoretical cross sections are to be reduced by a factor 9.)

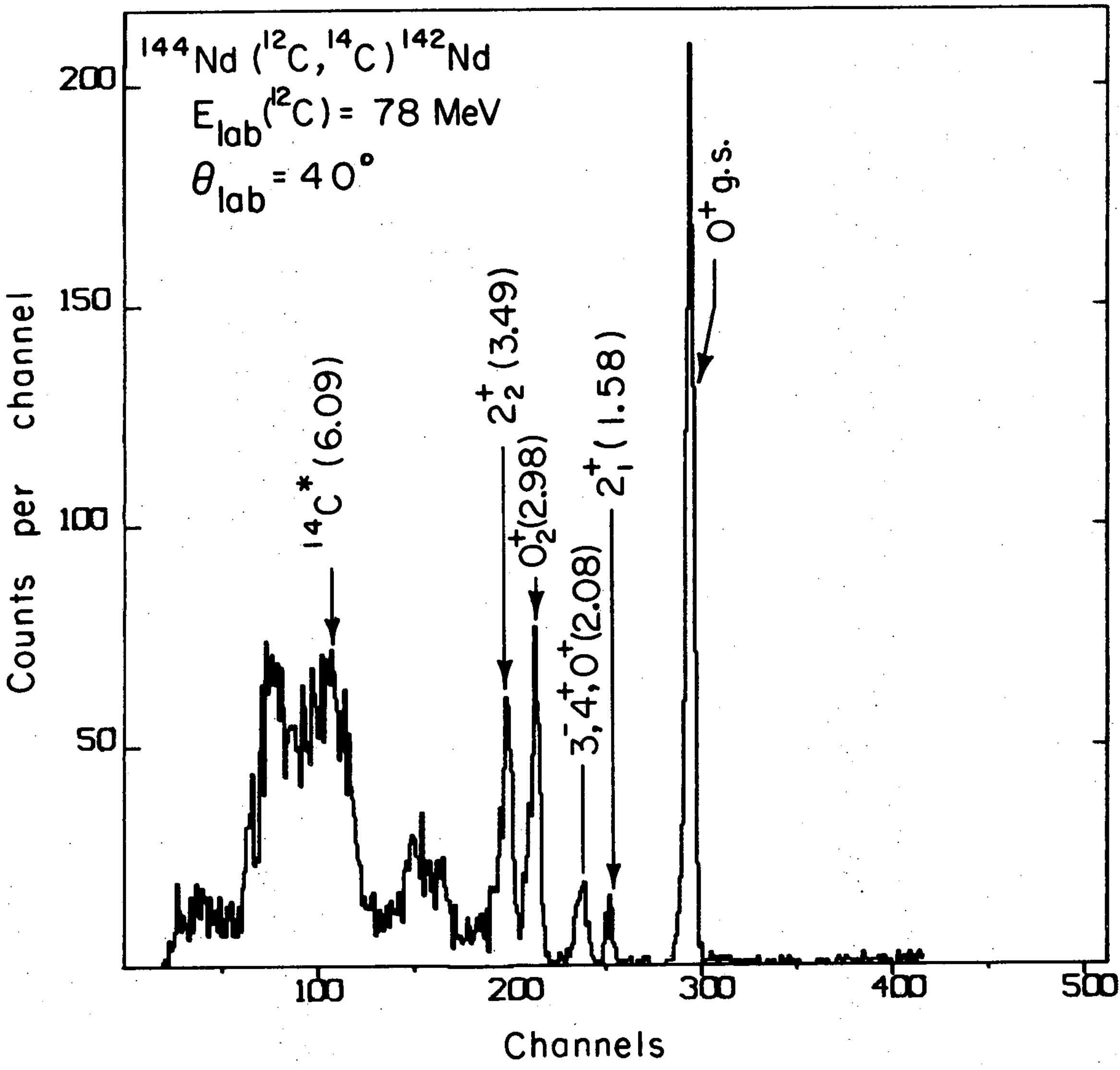
^{144}Nd (^{12}C,^{14}C)^{142}Nd
E$_{lab}$(^{12}C) = 78 MeV
θ$_{lab}$ = 40°
0$^+$ g.s.
2$_1^+$ (1.58)
3$^-$,4$^+$,0$^+$(2.08)
0$_2^+$(2.98)
2$_2^+$ (3.49)
^{14}C* (6.09)
Counts per channel
Channels
200
150
100
50
100
200
300
400
500
XBL745-3189

Fig. 1

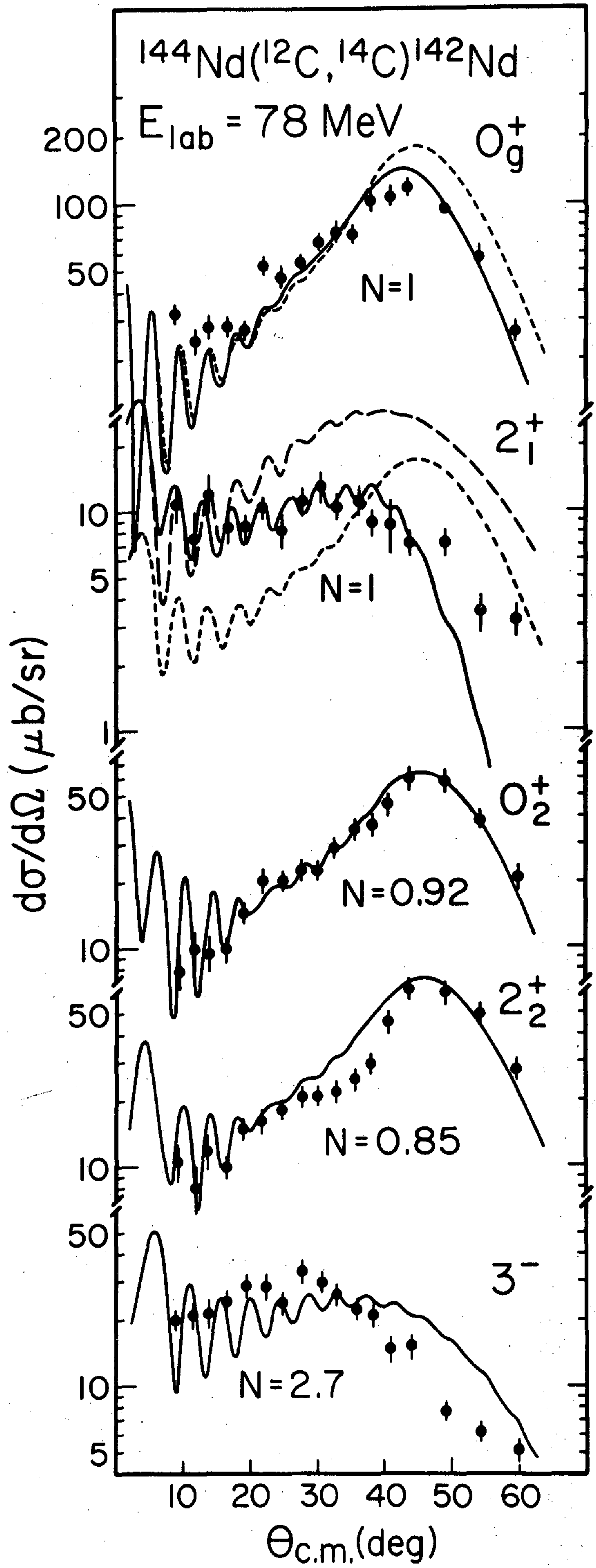
144Nd(12C,14C)142Nd
E lab = 78 MeV
0_g^+
N=1
2_1^+
N=1
0_2^+
N=0.92
2_2^+
N=0.85
3^-
N=2.7
200
100
50
10
5
1
50
10
50
10
50
10
5
dσ/dΩ (μb/sr)
10
20
30
40
50
60
θc.m.(deg)

Fig. 2

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