Inverse α Decay via the Reaction $^{208}Pb(^{16}O, ^{12}C)^{212}Po$

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We have measured the reaction $^{208}Pb(^{16}O, ^{12}C)^{212}Po$ at $E_{^{16}O} = 93$ MeV; the peak cross sections leading to the ground and first excited states of ^{212}Po are 750 and 1750 nb/sr, respectively. The reaction mechanism appears to be direct and excellent distorted-wave Born-approximation fits to the data yield a spectroscopic ratio of $S(0.727\ \text{MeV}, 2^+)/S(\text{g.s.}) = 0.64 \pm 0.13$ in good agreement with the value 0.61 ± 0.24 derived from ^{212}Po α decay. Preliminary attempts at obtaining absolute α widths yield $\gamma_\alpha{}^2(^{212}Po(\text{g.s.})) \sim 1.4$ keV from both α decay and the transfer reaction.

In view of the potential value of α-transfer reactions as a spectroscopic tool it is important to gain a thorough understanding of the reaction mechanism. One stringent test is afforded by a comparison of these reactions with their presumed inverse process, α decay. Nuclei in the lead region are ideally suited for such a test; however, this requires the study of α-transfer reactions in a mass region far beyond that which has been studied before, a region where the peak cross sections are likely to be less than 1 μb/sr. The purpose of the present study was to measure the ratio of the spectroscopic factors for the ground and first excited state of ^{212}Po in the reaction $^{208}Pb(^{16}O, ^{12}C)^{212}Po$ and to compare it with the known α-decay data.

Recently[1] a distorted-wave Born-approximation (DWBA) analysis of data from the possible α-transfer reactions (^{16}O, ^{12}C), (^{12}C, ^{8}Be), and ($^{6}Li, d$), all measured on the same target, yielded spectroscopic ratios in quantitative agreement among themselves and also with SU(3) calculations for several ^{24}Mg-to-^{28}Si transitions. For this study we chose the (^{16}O, ^{12}C) reaction because it was expected to have the largest cross section[2] and to suffer the least from impurity reactions.

A 93-MeV $^{16}O^{7+}$ beam from the upgraded Chalk River MP tandem accelerator was used to bombard isotopically enriched (98.2%) ^{208}Pb targets of approximately 250 μg/cm^2 evaporated on 5-μg/cm^2 carbon backings. The beam intensity was kept below 100 nA to prevent puncturing the targets. The reaction products were analyzed with the QD^3 spectrometer[3] operated at a solid angle of 11 msr. The movable focal-plane detector consisted of a 12-cm-long, 1.5-cm-thick proportional counter, in front of two 5-cm-long position-sensitive semiconductor detectors (PSD) mounted end to end. The geometry was such that the $^{12}C^{6+}$ ions from the ground and first excited states of ^{212}Po were each centered on a different PSD. Particle identification was achieved with a two-step procedure: (i) The ΔE and E signals from the proportional counter and PSD's, respectively, were used to find the atomic number Z [see Fig. 1(a)] by a range-table lookup procedure[4]; the table used was that of Northcliffe and Schilling[5] for ^{12}C. (ii) The mass could then be *uniquely* determined from the E signal since the momentum was nearly constant [see Fig. 1(b)]. A composite ^{12}C position spectrum derived from both PSD's is shown in Fig. 1(c); the energy resolution was about 250 keV. This spectrum, which is a kinematically compensated sum of three angles, represents a total of 30 h of data accumulation. The spectrometer was calibrated by elastically scattering 78-MeV $^{16}O^{7+}$ ions from the same ^{208}Pb targets.

A ΔE-E counter telescope in the scattering chamber was used to normalize the observed counts to the Rutherford cross section. This

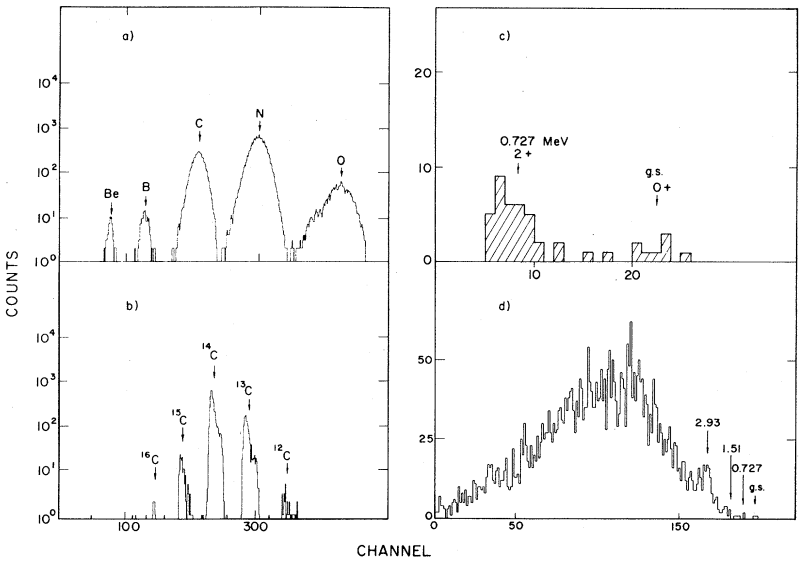

FIG. 1. (a) ΔE-E particle identification spectrum from one of the two position-sensitive detectors; $E_{^{16}O} = 93$ MeV, $\theta_{lab} = 80°$. (b) Energy spectrum at constant momentum gated on the C peak of 1(a), used to identify ^{12}C uniquely. All isotopes are in the 6^+ charge state. (c) Composite ^{12}C position spectrum from both position-sensitive detectors summed over three runs taken at 55.5°, 65°, and 78° in the lab. (d) ^{12}C spectrum from the monitor telescope at a laboratory angle of 65°.

telescope, with a solid angle of 2.8 msr, also allowed the observation of the complete ^{12}C spectrum but with a resolution of only 400 keV [see Fig. 1(d)].

The angular distributions for the ground and first excited states of ^{212}Po are shown in Fig. 2. These distributions are similar in shape to those from the (^{16}O, ^{15}N)[6] and (^{16}O, ^{14}C)[7] reactions on Pb at comparable energies. Thus the reaction ^{208}Pb(^{16}O, ^{12}C)^{212}Po also appears to proceed via a direct-transfer mechanism and shows no shape differences for different transferred angular momenta. The peak cross sections leading to the ground and first excited states are seen to be about 750 and 1750 nb/sr, respectively. Dividing by the $2J_f + 1$ factor, from first-order perturbation theory, we find that the first excited state of ^{212}Po is about 0.5 as strong as the ground state.

It is possible to derive a "reduced α width" ratio for the ^{212}Po(0.727 MeV, 2^+) and ^{212}Po(g.s.) states from their decay to the ^{208}Pb ground state by using the simple formula

$$\delta^2 = h/\tau P,$$

where τ is the mean life and P the penetrability. For the penetrabilities we took the original results of Rasmussen[8] based on WKB calculations using the real surface part of a simple optical potential but checked them with WKB calculations using more recent optical potentials[9] for α + Pb.

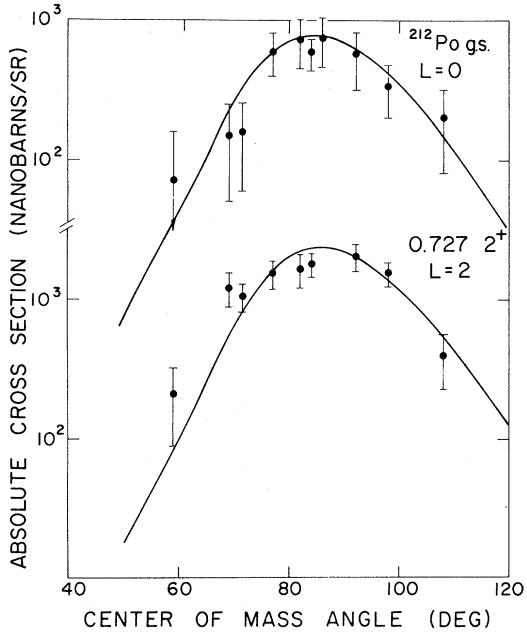

FIG. 2. Angular distributions of ^{12}C leading to the ground and first excited states of ^{212}Po. Solid lines are the results of exact recoil DWBA calculations normalized to the data.

The latter calculation gave very different absolute penetrabilities but the ratio for the two states, $P(\text{g.s.})/P(2^+)=0.037$, differed by less than 25%. The mean life of the ^{212}Po(g.s.) is known[8] but the value for the first excited state has not been measured and was derived indirectly. Effective $E2$ matrix elements have been found[10] which when used with the Kuo-Herling wave functions yield $B(E2)$ values in good agreement with those observed for the ^{210}Po $8^+ \rightarrow 6^+$, $6^+ \rightarrow 4^+$, and $4^+ \rightarrow 2^+$ transitions. If we use the predicted $2^+ \rightarrow 0^+$ $B(E2)$ value for ^{210}Po ($262e^2$ fm^4) and correct for the different ^{212}Po(2^+) excitation energy using the wellknown[11] E_γ^{-1} rule, then the resulting half life of 6.6 psec for the 2^+ level of ^{212}Po is expected to be accurate to better than $\pm 30\%$. The experimental α-γ branching ratio[8] thus gives an α half life of 18 nsec. The ratio of reduced widths is then found to be $\delta^2(2^+)/\delta^2(\text{g.s.})=0.61\pm0.24$ which can be compared with the approximate ratio (0.5) obtained above for the (^{16}O, ^{12}C) reaction.

A more quantitative description of the (^{16}O, ^{12}C) reaction was obtained from calculations using the DWBA code LOLA.[12] The assumption of an α particle in its ground state leads to a $3S$ relative motion for the $^{16}\text{O}=^{12}\text{C}+\alpha$ system and $12S$ or $11D$ relative motion for the ^{212}Po states. The Woods-Saxon potential parameters of Ref. 2 were used for both bound states, i.e. a radius of $1.25A^{1/3}$ fm and a diffuseness of 0.65 fm. The known $^{12}\text{C}+\alpha$ binding energy determined the ^{16}O well depth. Since ^{212}Po is unbound we arbitrarily chose a binding energy of 0.1 MeV. Calculations using larger binding energies showed that the shapes of the angular distributions are not sensitive to this parameter while the magnitude is a smooth exponential function of the binding energy, allowing a simple correction to be made to the magnitudes. The difference in binding energies between the ^{212}Po ground and first excited states is small so the correction factor (2^+/g.s. = 1.13) does not appreciably change the predicted cross-section ratio. The interaction potential is in the post representation and includes all Coulomb-interaction potentials.[13] The incoming and outgoing distorted waves were generated from an optical potential[6,7] ($V=40$ MeV, $W=15$ MeV, $r_0=1.31$ fm, and $a=0.45$ fm) which fits ^{16}O and ^{12}C elastic scattering from lead at nearby energies. The resulting fits are shown in Fig. 2 where the theoretical cross sections have been integrated over the 5.7° acceptance angle of the spectrometer.

Normalization of the DWBA predictions to experimental cross sections yields a ratio of spectroscopic factors of $S(2^+)/S(\text{g.s.})=0.64\pm0.13$ which is to be compared with the α-decay ratio of 0.61 ± 0.24. The error estimate (±0.13) includes counting statistics only. The ratio was not found to be particularly sensitive to different choices of bound states and/or distorted-wave parameters. We also note that our preliminary results on ^{207}Pb(^{16}O, ^{12}C)^{211}Po indicate a spectroscopic ratio $S(^{211}\text{Po(g.s.)})/S(^{212}\text{Po(g.s.)})=0.4\pm0.4$ in reasonable agreement with the α-decay ratio $\delta^2(^{211}\text{Po(g.s.)})/\delta^2(^{212}\text{Po(g.s.)})=0.1\pm=0.05$, derived from the data of Ref. 8.

Finally we report on our preliminary attempts to obtain an absolute α width for the ^{212}Po(g.s.); a detailed description will be given later. The nuclear potential of Barnett and Lilley[14] was used to generate both the penetrability and a resonant-state wave function for the $^{208}\text{Pb}+\alpha$ system. All the other parameters for the α decay and transfer reactions were the same as above. Using the formulas of Rasmussen[15] and Thompson, Adams, and Robson,[16] with $S(^{16}\text{O})=0.5$, we obtain $\gamma_\alpha^2(\alpha\text{ decay})=1.3$ keV and $\gamma_\alpha^2(\alpha\text{ transfer})=1.5$ keV. This surprisingly good agreement is subject, presumably, to large uncertainties which are in the process of being determined.

In conclusion, good DWBA fits to the data coupled with the agreement of absolute γ_α^2 and, most importantly, the excellent correspondence of the ratio $S(2^+)/S(\text{g.s.})$ between α-decay and transfer data suggests that a simple one-step transfer of a ground-state α particle dominates the reactions studied here.

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Unsurprising Aspects of Heavy-Ion–Induced Two-Nucleon Transfer Reactions*

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An apparent puzzle concerning the suppression of heavy-ion–induced *nn* and *pp* transfers compared to *np* transfer in light nuclei can be explained to a great extent by invoking simple arguments based on the binding energies of the transferred pairs to the two cores. The manifestation of this effect is in the tail regions of the appropriate bound-state wave functions where transfer is well known to occur. These arguments may be extended to include multinucleon transfers where the consequences of this effect could be even more drastic.

Recently, Anyas-Weiss *et al.*[1] have presented data concerning two-nucleon transfer reactions on light nuclei induced by high-energy (≈ 10 MeV/nucleon) heavy ions. It was observed in these studies that the *nn* and *pp* transfer reactions had differential cross sections of the order of 20 μb/sr whereas the *np* transfer differential cross sections were typically 1 mb/sr. They have generalized this result by concluding that the cross sections for $T=0$ transfer are much larger than those for $T=1$ transfer and that for *np* transfer the $T=1$ part may be neglected. While it may be useful to have such empirical rules, it is important to investigate other causes for such differences in cross sections.

In the present study, we report experimental and theoretical results on ^{12}C(^{14}N, ^{12}C)^{14}N, ^{12}C(^{14}N, ^{12}N)^{14}C, and ^{12}C(^{14}N, ^{12}B)^{14}O at 155 MeV as well as some theoretical calculations on three-nucleon transfer data.

A 200-μg/cm^2-thick natural carbon target was bombarded by 155-MeV ^{14}N ions from the Texas A & M cyclotron. Energy spectra obtained simultaneously for the ^{12}C, ^{12}B, and ^{12}N exit channels at $\theta_{lab} = 5.5°$ using standard particle identification techniques[2] are shown in Fig. 1. The present spectrum for the reaction ^{12}C(^{14}N, ^{12}C)^{14}N is similar in its general features to the one taken at 118 MeV by the Oxford University group.[1] However, because of the improved energy resolution of our spectrum (~ 350 keV), additional information can be obtained from our data. Results for comparison are also available from studies on the reaction ^{12}C(α, d)^{14}N.[3] We note that the ^{12}C(^{14}N, ^{12}C)^{14}N channel can in principle include backward elastic and inelastic scattering. However, the selective population of final states (Fig. 1) and the strong forward peaking of their angular distributions (Fig. 2) demonstrate that the reaction is a direct transfer process.

In Fig. 1, the spectra of the (^{14}N, ^{12}B) and (^{14}N, ^{12}N) reactions are inserted for comparison. In the ^{12}N spectrum scattered background counts were recorded due to Landau fluctuations from the very large counting rates in the ^{14}N and ^{13}N channels although the particle identification system was very carefully set. Thus the ground states of ^{14}C and ^{14}O could hardly be seen above the background. Nevertheless, several transitions to the known states in ^{14}O and ^{14}C were ob-