Excitation functions for ^{7}Be production by light-ion bombardment of ^{12}C†

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We have measured excitation functions for production of ^{7}Be by d-, ^{3}He-, and α-particle-induced reactions in carbon using the stacked-foil method. Similar measurements for protons were obtained earlier. For each particle the data extend beyond 75 MeV. The ^{7}Be yields approach zero, respectively, in the neighborhood of threshold energies for the (p, ^{6}Li), (d, ^{7}Li), (^{3}He, ^{8}Be), and (α, ^{9}Be) reactions. The p- and ^{3}He-induced yields have similar energy dependences, peaking at roughly 10 MeV above threshold; in contrast, the maximum cross sections for the d and α curves occur 30–50 MeV above threshold energies. The maximum yield from ^{3}He-induced reactions (98 mb) is about a factor of 3 larger than that for p, d, or α. These results suggest that α-particle pickup may be an important part of the ^{7}Be yield at the lower energy part of the ^{3}He excitation function.

[NUCLEAR REACTIONS ^{12}C(d, x), ^{12}C(^{3}He, x), ^{12}C(α, x); $E \sim 20–80$ MeV; measured $\sigma(E)$; Ge(Li) detector. Deduced reaction mechanism.]

INTRODUCTION

Nuclear reaction excitation functions depend to some extent on reaction mechanisms. The isotope ^{7}Be is the only long-lived γ-ray emitter of low mass and consequently excitation functions for its production in charged particle reactions are easy to measure. The present work presents the results of measurements of such excitation functions and also attempts to draw inferences on reaction mechanisms from them.

We have measured excitation functions for production of ^{7}Be in carbon targets bombarded with deuterons, ^{3}He, and α particles. Similar measurements were reported earlier for proton-induced reactions.[1] The pronounced differences in the low energy portions of the various excitation functions suggest that additional reaction modes are involved in the ^{3}He- and proton-induced yields and appear to be the dominant modes in these energy regions. Moreover, the low energy enhancement of the ^{3}He-induced yield relative to that induced by protons suggests yet an additional mechanism for the former reactions. We suggest that α-particle pickup may be such a mode.

EXPERIMENTAL

Stacked carbon foil targets were exposed to incident particle beams at the Oak Ridge isochronous cyclotron and the University of Maryland cyclotron. The target holders were electrically insulated and served as Faraday cups to monitor the incident beams with an accuracy of ~1%. For each bombardment an integrated beam of between 10^{14} and 10^{15} particles was used. Subsequently γ-ray spectra of individual target foils were measured to determine the ^{7}Be yields.

Target foils 15.6 and 24.5 mg/cm^2 thick were used. For the higher energy deuteron data thicker carbon wafers (287 mg/cm^2) were sandwiched between neighboring foils; spectra from the thin foils were used. The energy of the incident beam particles at the midpoint of each target foil was determined from range-energy tables. The uncertainty of particle energy for each data point is due to energy spread of the incident beam (±0.2%) and energy-loss straggling. The latter can be appreciable for foils deep in the target stack. By use of a number of bombarding energies for each particle type the effects of energy-loss straggling were kept to less than 0.7 MeV.

The Ge(Li) detector used to measure the spectra was calibrated for efficiency with a number of γ-ray sources of known intensity. Since variation in detector geometry could be a significant source of error in the measurements, spectra for each foil were measured twice, at different times, to check the reproducibility of the data; variation was less than 10% in all cases.

RESULTS AND DISCUSSION

The measured excitation functions are presented in Fig. 1, which also includes the proton data from Ref. 1. The solid line at the low energy part of the ^{3}He data represents measurements reported by England and Reece,[2] and the 100 MeV point in the α-particle data is from the work of Gauvin.[3] Although measurements were not made between 66 and 87 MeV for ^{3}He particles, the data shown in Fig. 1 suggest there is little structure in that region of the excitation function.

Errors in the absolute cross sections are less than 10% in the flat portions of the excitation functions. In the steep portions of the curves uncertainties in incident particle energy due to straggling result in errors as large as a factor of 2. This is most apparent in the deuteron data.

The ^{7}Be yields approach zero, respectively, in the neighborhood of the threshold energies for the $(p, {}^{6}\text{Li})$, $(d, {}^{7}\text{Li})$, $({}^{3}\text{He}, {}^{8}\text{Be})$, and $(\alpha, {}^{9}\text{Be})$ reactions in ^{12}C. The proton and ^{3}He curves are similar in shape and peak roughly 10 MeV above threshold energies. The d and α curves rise more gradually with maximum yields of ^{7}Be at 30 to 50 MeV above threshold energies. The maximum yield from ^{3}He-induced reactions is a factor of 3 or more larger than that for p-, d-, or α-particle-induced reactions.

Cochran and Knight[4] have measured the excitation function from threshold to 24 MeV and England and Reece[2] have further investigated the excitation function and the angular distribution and energy spectra of ^{7}Be produced by ^{3}He bombardment of ^{12}C at energies below 30 MeV. The authors of Ref. 2 have proposed that the ^{7}Be is produced principally in a three-body reaction i.e., the reaction may take place through formation of an ^{15}O compound system which evaporates two α particles, or through a neutron pickup reaction where the ^{11}C residual nucleus decays by α-particle emission to ^{7}Be. In Ref. 2 the authors did not consider the mechanism of α-particle pickup by the incident ^{3}He particle.

In Fig. 2 the measured excitation function for ^{3}He incident particles is compared with calculated α-particle emission probability for the $^{3}\text{He} + {}^{12}\text{C}$ compound system.[5] The shapes of the two yield curves are similar at incident particle energies larger than ~45 MeV but very different at lower energies, especially near the peak of the ^{7}Be yield. It thus appears that emission of two α particles from the ^{15}O compound system is not the dominant mode for production of ^{7}Be near the peak of the excitation function. We note that the predicted α-particle yield in Fig. 2 resembles that of the ^{7}Be yield curves for deuteron and α-particle-induced reactions (Fig. 1), indicating that α-particle evaporation may well be an important mechanism in those reactions.

The similarity in shape of the excitation functions for proton- and ^{3}He-induced ^{7}Be production reactions suggests there may be a similarity in the dominant reaction modes, especially for the lower energy parts of the yield curves. One such mechanism would encompass reactions that yield ^{11}C with enough excitation energy to emit an α particle and leave a residual ^{7}Be nucleus. The reactions (p, d) and $({}^{3}\text{He}, \alpha)$ on ^{12}C both produce ^{11}C. It is well known, however, that (p, d) reactions have small cross sections, especially for high excitation of the residual nucleus. The reaction $^{12}\text{C}(p, pn)^{11}\text{C}$ would result in a higher relative

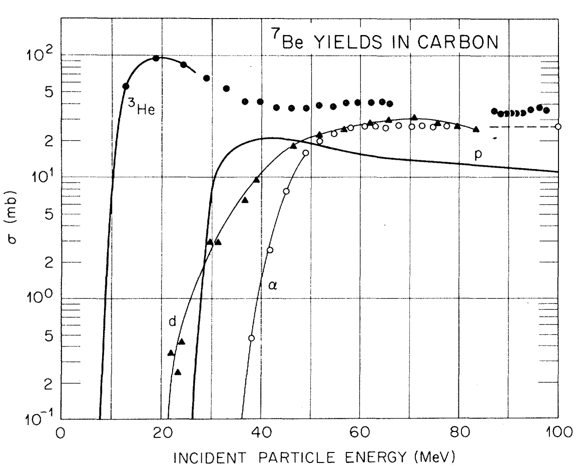

FIG. 1. Excitation functions for production of ^{7}Be by proton-, deuteron-, ^{3}He-, and α-particle-induced reactions in carbon. The proton data are from Ref. 1; the solid line in the ^{3}He data is from measurements reported in Ref. 2, and the 100 MeV α-particle datum is from Ref. 3.

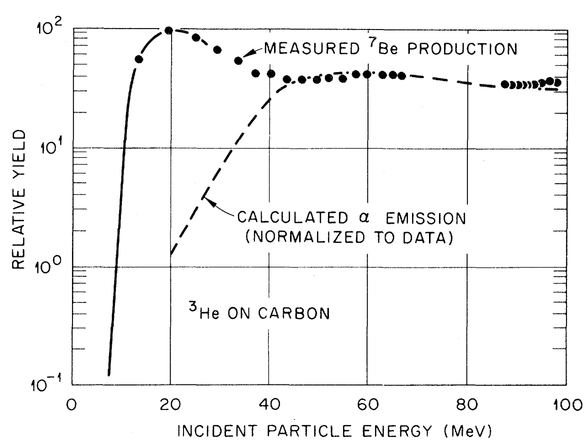

FIG. 2. Excitation function for production of ^{7}Be by ^{3}He-induced reactions in carbon compared with calculated α-particle emission probability for the $^{3}\text{He} + {}^{12}\text{C}$ compound system. The curves are normalized in the flat portions for comparison.

yield of ^{11}C with enough excitation to emit an α particle.

The $^{12}C(p,pn)^{11}C$ cross section has been measured over a wide range of energy.[6,7] In Fig. 3 we compare the excitation function for production of ^{7}Be by proton-induced reactions in carbon with that for production of ^{11}C by $^{12}C(p,pn)$ reactions. Calculated yields of both reaction products obtained from intranucleon cascade followed by evaporation[8] are also shown for a few energies: The calculations do not include reaction thresholds. The calculated yields follow the general trend of the excitation functions at energies above the maximum yields with substantially better agreement with measurements of ^{11}C yields. The similarity of the shapes of the yield curves for ^{11}C and ^{7}Be and the magnitudes of the relative cross sections suggest, we believe, that α-particle evaporation from ^{11}C is an important mode for production of ^{7}Be by proton-induced reactions in carbon targets, with the population of levels in ^{11}C occurring via either direct knockout or neutron evaporation.

We now consider whether similar reaction modes can account for the low energy part of the ^{3}He-induced excitation function. First of all, we note that even if the ^{7}Be production results from α decay of ^{11}C, the population of those levels at the lower incident energies cannot proceed via neutron knockout, since the threshold for $^{12}C(^{3}He, {}^{3}He\,n)^{11}C$ g.s. is 23.4 MeV (lab). Figure 4 compares the excitation function for ^{7}Be by ^{3}He-induced reactions in carbon with that for ^{11}C. The ^{11}C yield below 30 MeV was reported by Brill[9] and is due to $(^{3}He, \alpha)$ reactions. The ^{11}C yield above 40 MeV is from the work of Crandall *et al.*[10] and is largely the result of $^{12}C(^{3}He, {}^{3}He\,n)$ reactions. We note that the shape of the ^{11}C yield curve, for energies below 30 MeV, is very different from that calculated for α-particle emission from the $^{3}He + {}^{12}C$ compound system (Fig. 2). The ^{11}C yield peaks at 10 MeV with a cross section of 260 mb and falls to a value near that for ^{7}Be at 20 MeV; at higher energies the yields of ^{11}C and ^{7}Be are comparable. A comparison of the yield curves in Fig. 3 with those in Fig. 4 suggests that α-particle emission from reactions that lead to ^{11}C cannot be as important a mechanism for forming ^{7}Be in ^{3}He-induced reactions as it is for those induced by protons. While the ^{11}C yield does peak significantly at low energies, by 18 MeV the yield has dropped to less than a factor of 2 greater than that of ^{7}Be; from Fig. 3, we see that roughly a factor of 5 is required if ^{11}C is to be regarded as a principal "source" of ^{7}Be.

We now consider the possibility of a direct reaction mechanism leading to production of ^{7}Be. The two possible modes in this category would be the "direct pickup," the formation of ^{7}Be through pickup of ^{6}Li, ^{5}Li, ^{4}He, and ^{3}He, by p, d, ^{3}He, and α, respectively, and the so-called "exchange pickup" with the incident projectile picking up a ^{5}He cluster from the target and leaving behind a ^{7}Be core. The latter mode seems a doubtful candidate, as appreciable ^{5}He cluster substructure in the target seems to be unlikely.

By a similar argument, one might expect that of all the direct pickup reactions, the $(^{3}He, {}^{7}Be)$ would be the most likely, with α-particle cluster substructure appearing to be more likely than ^{6}Li, ^{5}Li, or ^{3}He. Evidence of α-particle substructure has in fact been seen in other reactions.[9,11] Moreover, such a direct reaction mode would be ex-

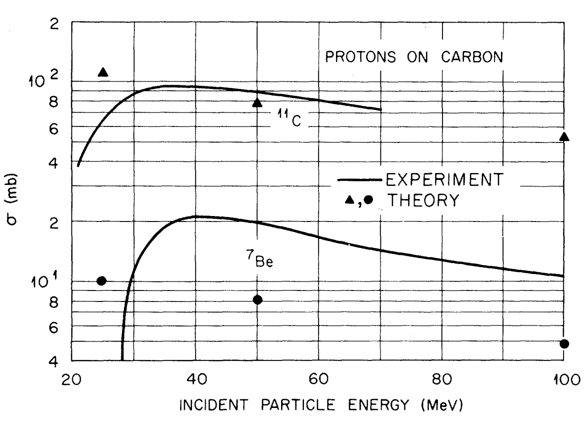

FIG. 3. Excitation functions for production of ^{11}C and ^{7}Be by proton-induced reactions in carbon. The ^{11}C data are from Refs. 6 and 7 and the ^{7}Be data are from Ref. 1. The points shown as triangles and circles are calculated values described in the text.

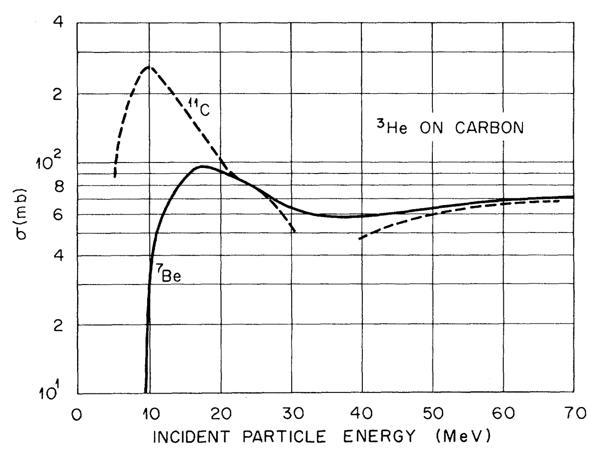

FIG. 4. Excitation functions for production of ^{11}C and ^{7}Be by ^{3}He-induced reactions in carbon. The ^{11}C data below 30 MeV are from Ref. 9 and above 40 MeV are from Ref. 10.

pected to become less important at higher energies,[12] as the angular momentum mismatch becomes more severe; this is consistent with the reduction in the enhancement of the ^{3}He-induced yield of ^{7}Be at higher energies.

CONCLUSIONS

Induced yields of ^{7}Be by ^{3}He and proton bombardment show peaking at energies slightly above threshold, whereas those of d and α bombardment show gradual rises to energies roughly 20–50 MeV above threshold. The latter yields are consistent with evaporation processes, a mechanism which is also adequate to explain the higher energy portions of the ^{3}He- and p-induced yields. The proton-induced ^{7}Be yields are consistent with population of α-unstable levels in ^{11}C, possibly via the ^{12}C(p, pn)^{11}C* reaction. While population of α-unstable levels in ^{11}C could conceivably occur in the ^{3}He-induced reactions, the low energy enhancement of the ^{3}He-induced yield relative to that of protons suggests a "unique" mechanism for the former, for which we suggest a likely candidate is the reaction ^{12}C(^{3}He, ^{7}Be)^{8}Be. The reduction in enhancement of the ^{3}He-induced yield with energy is also consistent with the enhancement being due to a direct reaction mechanism. (Unexplained as yet is the apparent persistence of roughly 25% enhancement for the ^{3}He-induced yield at higher energies, which appears to be somewhat larger than that which can be attributed to errors in normalization of absolute cross section.) Pursuant to our speculation, it would be interesting to perform the ^{12}C(^{3}He, ^{7}Be)^{8}Be reaction in the neighborhood of $E_{\rm lab} = 20$ MeV to see if in fact the conjectured increase in direct-reaction cross section does occur.

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[1]I. R. Williams and C. B. Fulmer, Phys. Rev. 154, 1005 (1967).

[2]J. B. A. England and B. L. Reece, Nucl. Phys. 72, 449 (1965).

[3]H. Gauvin, Institute de Physique Nucléaire Orsay report; and reported in the paper by P. Fontes, C. Perron, J. Lestzingues, F. Yiou, and R. Bernas, Nucl. Phys. A165, 405 (1971).

[4]D. R. F. Cochran and J. D. Knight, Phys. Rev. 128, 1281 (1962).

[5]The calculations were performed with the compound nucleus evaporation code EVAP-4, a revision of the code EVAP, L. Dressner, ORNL Report No. ORNL-TM-196, 1961 (unpublished). The calculation is based on a theory originally proposed by V. F. Weisskopf, Phys. Rev. 52, 295 (1937), and a Monte Carlo code written by Dostrovsky, Phys. Rev. 116, 683 (1959); 118, 781, 791 (1969).

[6]J. B. Cumming, Nucl. Phys. 49, 417 (1963) and references contained therein.

[7]N. M. Hintz and N. F. Ramsey, Phys. Rev. 88, 19 (1952).

[8]H. W. Bertini, private communication. For a description of the calculation see H. W. Bertini, Phys. Rev. 131, 1801 (1963); 138, AB2(E) (1965).

[9]O. B. Brill, Yad. Phys. 1, 55 (1965) [transl.: Sov. J. Nucl. Phys. 1, 37 (1965)]. The authors of Ref. 4 also measured the excitation function to $E = 24$ MeV for production of ^{11}C by ^{3}He-induced reactions in carbon. The maximum cross section, at 9.5 MeV, is ~ 340 mb and there is some indication of structure in the excitation function. The general shape and magnitude, however, is similar to that of the most recent measurements of Brill which is shown in Fig. 4.

[10]W. E. Crandall, G. P. Milburn, R. V. Pyle, and W. Birnbaum, Phys. Rev. 101, 329 (1956).

[11]C. Detraz, H. H. Duhm, and H. Hafner, Nucl. Phys. A147, 488 (1970).

[12]From Ref. 11, one can estimate that when the incident energy is as large as 30 MeV, the total ^{7}Be yield cross section is less than or equal to 10 mb.