FORMATION OF ^7Be IN NUCLEAR REACTIONS
INDUCED BY 85-MeV PROTONS

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by

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I. INTRODUCTION

The emission of multiply-charged fragments ($Z > 3$) in nuclear reactions was first recorded by Perkins⁽¹⁾ who studied disintegrations caused by cosmic rays. Subsequently the production of complex particles has been observed in many nuclear reactions induced by projectiles with a wide range of energies. The emission of these fragments has been investigated with respect to fragment yield, charge, energy, and angular distribution, using counter, radiochemical, and emulsion techniques.

The majority of emitted fragments have nuclear charges of 3 to 8⁽²⁾, and the following discussion is concerned with fragments in this charge range.

A. OBSERVED CHARACTERISTICS OF FRAGMENT EMISSION

1. Excitation Functions

The cross-section for fragment production from Ag and Br nuclei has been obtained, as a function of energy, by means of emulsion techniques.⁽³⁾ The yield increases smoothly with proton energy but undergoes a sharp increase at 400 MeV.

The variation of fragment cross-section with target mass has been determined mainly at high energies by counter, radiochemical, and emulsion techniques. If one plots these cross-sections versus mass number, an initial decrease is observed. This is associated with the production of fragments

as spallation residues. The variation of cross-section with target mass for mass numbers greater than 20 is dependent on the neutron-to-proton ratio of the emitted fragment and the target itself. At high incident proton energies (BeV range) the yield of neutron-deficient fragments, e.g. ${}^7\text{Be}(4,5)$, ${}^{11}\text{C}(5,6)$, ${}^{13}\text{N}(5,7)$, was found to decrease with increase in target mass number and the yield of neutron-rich fragments, e.g. ${}^6\text{He}(8)$, ${}^8\text{Li}(7,9)$, ${}^9\text{Li}$, ${}^{17}\text{N}$, ${}^{16}\text{C}(10)$, to increase with increase in mass number. The yield of fragments near stability, e.g. ${}^{18}\text{F}$, ${}^{24}\text{Na}(5,11)$ was found to decrease to mass number $A \sim 150$ then to increase with further mass increase. Furthermore Dostrovsky et al.⁽¹⁰⁾ found a strong dependence of the cross-section of ${}^9\text{Li}$, ${}^{16}\text{C}$, and ${}^{17}\text{N}$ on the neutron-to-proton ratio of the target for all mass regions (the incident protons had energies of 1 and 2.8 BeV). They studied pairs of targets close in mass number but different as far as possible in their neutron-to-proton ratio and found that a plot of cross-section against the neutron-to-proton ratio of the target yielded a smoother curve than a plot of cross-section versus mass number.

2. Charge Distribution

With the aid of emulsion techniques, the charge distribution (obtained by plotting fragment yield versus its charge) was found to vary little over a wide range of energy, from incident protons with 100 MeV energy⁽¹²⁾ to cosmic ray energies^(1,13). Perfilov et al.⁽²⁾ found that the total probability for the emission of particles of a given charge, P ,

could be related to their charge, Z , by an exponential relation of the type $P \sim \exp(-Z^n)$ where $n = 0.7$ to 1.0 .

Investigations with nuclear emulsions have yielded total cross-sections for fragments of a given nuclear charge. This cross-section is made up of a sum of the cross-sections of several isotopes. The use of radiochemical methods has yielded cross-sections for specific isotopes. Perfilov et al.⁽²⁾ noted that the total cross-section for complex particles of a given charge is always greater (10 to 50 times) than the cross-section of the individual radioactive isotope having the same charge. They attributed this difference to the fact that the principal part of the total cross-section is due to isotopes not detectable by radiochemical methods. Because of the small number of possible isotopes of light elements, they reasoned that the great difference between total cross-sections and cross-sections for individual isotopes could not be explained by assuming that all possible isotopes have approximately the same yield. Data of Sidorov and Grigor'ev⁽¹⁴⁾ further showed that the majority of emitted fragments are stable with respect to beta-decay. Perfilov and co-authors thus suggested that stable isotopes with a certain charge-to-mass ratio, Z/A , are favoured in fragment emission.

3. Energy Distribution

Emulsion studies have shown that the energy distribution of multiply-charged particles is characterized by the presence of fragments with energies both considerably greater and lower than the classical Coulomb barrier although the

greatest number of fragments is produced with energies near the Coulomb barrier.^(15,16) As the energy of the incident particle that induces the disintegration is increased (from 0.1 to 9.0 BeV), the most probable fragment energy remains the same. However, there is an increase in the relative number of particles with energies in great excess of the Coulomb barrier value.^(12,13)

4. Angular Distribution

The fragment distribution was found to become more and more isotropic as the incident energy increased. This is shown in Table I which gives the forward-to-backward ratio of fragments emitted in the disintegration of Ag and Br nuclei. The energy of the incident protons ranges from 76 MeV to 6.2 BeV. (Direction is defined with respect to the beam.)

TABLE I

ANGULAR DISTRIBUTION OF FRAGMENTS IN THE
DISINTEGRATION OF Ag and Br NUCLEI

<u>E</u> Proton Energy (MeV)	<u>F/B</u> Forward-to-Backward Ratio	<u>Reference</u>
76	33	16
100	6.3 $\pm$ 1.6	
200	3.9 $\pm$ 0.7	
350	3.0 $\pm$ 0.6	
	3.0	14
450	3.1	
660	2.8 $\pm$ 0.3	
950	2.5	17
6200	1.44	13

The forward-to-backward ratio has also been shown to be related to the target mass. The asymmetry in fragment distribution was found greater for light nuclei (C,N,O) than for heavy nuclei (Ag, Br) in emulsion.^(2,13,16) Katcoff, Baker, and Porile⁽¹⁸⁾ studied the angular distribution of ^8Li fragments emitted from Cu, Ag, and Au irradiated by 2 BeV protons and found that the forward peaking was greatest for the copper targets and least for the gold targets.

The same workers also found a relation between the asymmetry and the energy of the emitted fragment. For example, for Cu targets the forward-to-backward ratio of ^8Li fragments emitted with energy less than or equal to the peak energy was determined to be 1.5 while the forward-to-backward ratio of fragments with energy greater than the peak energy was 3.6.

5. Multiplicity

The probability of two or more fragments appearing in a single disintegration was found to increase greatly with increasing projectile energy. For protons of 660-MeV energy incident on Ag and Br nuclei, 5% of the fragment disintegrations occur with two or more fragments⁽¹⁵⁾; for 3-BeV protons the probability of emission of two fragments is greater than the probability of emission of one fragment.⁽¹⁹⁾

Interactions involving fragment emission were found to lead to a much larger number of emitted charged particles than are found in reactions not involving fragment emission. For example, for incident protons of 660-MeV energy, the average number of emitted charged particles in an ordinary interaction

is 3.5 while the average number of charged particles in an event with fragments is 6; for 460-MeV protons these values are 2.6 and 4.8 respectively. (15,20)

B. PROPOSED MECHANISMS FOR FRAGMENT EMISSION

There is no consensus on the mechanism of fragment emission; its characteristics have been explained both in terms of slow and fast reactions.

1. Fragment Emission a Slow Process

(i) The Statistical Model:

For low energy nuclear reactions the Bohr⁽²¹⁾ concept of the compound nucleus has proved useful. The incident particle with a certain kinetic energy impinges upon a system of nucleons along a particular entrance channel. The force binding the nucleons together is assumed to be strong and short-range in character. The energy and momentum of the incident particle are shared with all other nucleons through multiple collisions to form an equilibrium system, the compound nucleus. The excitation energy of the compound nucleus is equal to the kinetic energy plus the binding energy of the incident particle. The compound nucleus decays when a nucleon 'accidentally' accumulates enough energy to escape along a particular exit channel by random collisions among the nucleons. The lifetime of the compound nucleus is then long ($\sim 10^{-14}$ to 10^{-17} sec.) in terms of the nuclear relaxation time, the time for equilibrium to be established by collisions between the nucleons. Particle emission is characterized by the constants of motion (excitation

energy, momentum, and parity) and the size and shape of the compound nucleus, i.e. the decay is governed by phase space. There is no memory of the mode of compound nucleus formation. The description of a nuclear reaction in terms of the decay of an equilibrium system of long lifetime with the assumption of independence of formation and decay modes, in which phase relations can be neglected, is called the 'Statistical Model'.

At low excitation energy (< 1 MeV) the compound nucleus exists in certain discrete energy levels or states. With increasing excitation energy the lifetime of the compound nucleus, τ , decreases and the corresponding uncertainty in the energy of the compound nucleus, $\Gamma = \frac{\hbar}{\tau}$, increases. The level widths increase causing the levels to overlap.

It is possible to apply the well-known principle of detailed balance to the compound nucleus at low excitation energy⁽²²⁾; the transition probability of a state a to state b, ω_{ab} , is related to the transition probability from the state b to the state a, ω_{ba} , by

$$\rho_a \omega_{ab} = \rho_b \omega_{ba}^* \quad (1)$$

where ρ_a and ρ_b are the density of states a and b and the star on ω_{ba} indicates the time-reversed transition, i.e. the transition in which all velocities and orbital angular momenta have changed sign.

The application of equation (1) to the highly excited compound nucleus when several levels are within the width Γ ,

is complicated due to the occurrence of interference effects between the matrix elements. The basis of the statistical model is the assumption that the matrix elements have randomly distributed phases due to the randomized internal motion of the compound nucleus. The determination of cross-sections averaged over incident energy much larger than the width Γ will not depend on interference effects; all cross terms will disappear. In this energy interval equation (1) yields only an average transition probability. The assumption of random phases makes the compound nucleus analogous to a classical equilibrium system such as the evaporation of particles from a heated liquid drop (Bohr⁽²¹⁾).

The excited compound nucleus then decays by 'evaporation' of particles as long as energy is available for their emission. Because there are no phase relations between formation and decay modes, the angular distribution of the particles is symmetrical about 90° in the centre-of-mass system.

The starting point of evaporation calculations is the Weisskopf expression⁽²³⁾ (based on the principle of detailed balance) for $P_j(E_j)dE_j$, the probability per unit time that a nucleus will emit a particle j with kinetic energy between E_j and $E_j + dE_j$:

$$P_j(E_j)dE_j = \frac{g_j m_j}{\pi^2 \hbar^3} \cdot \sigma^*(E_j) \cdot \frac{\omega(E_f)}{\omega(E_i)} \cdot E_j \cdot dE_j \quad (2)$$

where $g_j = 2s_j + 1$ = number of spin states of particle j .
 s_j = spin (quantum number) of particle j .

m_j = mass of particle j .

$\sigma^*(E_j)$ = cross-section of inverse reaction.

$\omega(E_f), \omega(E_i)$ = level density of final and initial nuclei at their respective energies.

The resulting energy distribution of emitted particles is Maxwellian in character.

The integration of equation (2) over all possible energies gives the total emission width, Γ_j , for a particular particle j :

$$\Gamma_j = \hbar \int P_j(E_j) dE_j = \frac{g_j m_j}{\pi^2 \hbar^2} \int \sigma^*(E_j) \cdot \frac{\omega(E_f)}{\omega(E_i)} \cdot E_j \cdot dE_j \quad (3)$$

The cross-section for specific particle emission, σ_j , is then given by the ratio of the emission width for a particle to the sum of the emission widths of all other possible emitted particles, multiplied by the cross-section for the formation of the compound nucleus, σ_c , (at low excitation energy σ_c is assumed equal to the capture cross-section for the incident particle):

$$\sigma_j = \sigma_c \frac{\Gamma_j}{\sum_j \Gamma_j} \quad (4)$$

The angular distribution, energy distribution, and formation cross-section of particles emitted from a compound nucleus are thus predicted by evaporation theory. The dynamics of the decay are contained in the inverse cross-section while the remaining factors are due to available phase space. From

the phase space point of view there is no distinction between the emission of nucleons and complex particles. The probability that fragments are evaporated from a compound nucleus in competition with lighter particles is inhibited by high Coulomb barriers and Q-values but favoured by the statistical factor $g_j m_j$. The mass, m_j , is proportional to the mass number, A, and the spin, s_j , is often large. The emission of excited states of complex particles also contributes to their formation cross-section.

Experimental data for fragment emission in reactions produced by low-energy (< 60 MeV) particles incident on light elements have been explained in terms of evaporation theory. Lindsay and Carr⁽²⁴⁾ compared the excitation function of the reaction $^{27}\text{Al}(\alpha, ^7\text{Be})^{24}\text{Na}$ with evaporation calculations and found at least qualitative agreement. Their study of the bulk ($0 - 90^\circ$, $90 - 180^\circ$ laboratory angle) distribution by the catcher-foil technique indicated the reaction to proceed through a compound nucleus. However, Porile⁽²⁵⁾ studied the recoil properties of ^7Be formed by the 40-MeV alpha particle bombardment of aluminum and concluded that the results were consistent with approximately equal contributions from evaporation and some direct process. Hower⁽²⁶⁾ irradiated light nuclei with 42-MeV alpha-particles and found the ^7Be energy spectra to resemble evaporation spectra. The existence of the compound nucleus in the process of fragment emission induced by low-energy particles was tested by Lindsay and Neuzil.^(27,28) They compared the excitation function for the reaction $^{51}\text{V}(p, ^7\text{Be})$ with that for

$^{48}\text{Ti}(\alpha, ^7\text{Be})$ and the excitation function for the reaction $^{27}\text{Al}(p, ^7\text{Be})$ with that for $^{24}\text{Mg}(\alpha, ^7\text{Be})$.⁽²⁴⁾ In each case the same compound nucleus was formed. However, the alpha-particle induced reaction cross-sections were greater than the proton-induced cross-sections by a factor of five or more. Neuzil and Lindsay⁽²⁸⁾ postulated that the higher average angular momenta of the alpha-induced reaction favour the emission of a heavy fragment which may carry off a large orbital angular momentum. Furukawa, Kume, and Ogawa⁽²⁹⁾ also studied the excitation function for the reaction $^{27}\text{Al}(p, ^7\text{Be})$ and found fair agreement with the data of Lindsay and Neuzil.^(27,28) Their comparison of this excitation function with that of the reaction $^{24}\text{Mg}(\alpha, ^7\text{Be})$ measured by Lindsay and Carr⁽²⁴⁾ showed the cross-section for the alpha-induced reaction to be larger than the proton-induced reaction by a factor of ten at the same excitation energy of the compound nucleus. Furukawa et al. concluded that the compound nucleus process was not valid in this case.

(ii) Cascade-Evaporation:

High energy nuclear reactions cannot be interpreted in terms of compound nucleus formation. The wavelength of the incident particle is short compared to nuclear dimensions; the particle collides with the individual nuclear nucleons or even passes right through the nucleus. The energy of the incident particle is great enough so that in a two-body collision the force of the other nucleons may be neglected and the collision considered a collision between free nucleons. According to

this picture, the incident particle enters the nucleus and collides with a nucleon. Either of the collision partners, depending on its energy and position in the nucleus, may escape the nucleus or collide with a further nucleon. An intranuclear cascade of fast neutrons and protons is thus generated in which, however, each collision is governed by the Pauli exclusion principle. The cascade process continues until the energy of the collision partners is such that the force of the other nucleons on the collision can no longer be neglected and so-called 'prompt' particles are no longer emitted. The residual nucleus is left in an excited state whose excitation energy is determined by the development of the cascade. Residual nuclei thus formed now de-excite in the same way as the compound nucleus - by the evaporation of particles. The evaporation is entirely analagous to the process described by the statistical model.

Fragment emission induced by high-energy particles has been explained in terms of cascade-evaporation on the assumption that fragment emission does not occur during the cascade phase of the reaction. Approximate cascade-evaporation calculations of fragment emission were done by Hudis and Miller⁽³⁰⁾ to predict formation cross-sections of ^7Be in high-energy nuclear reactions. The calculated cross-sections were found to describe the shape and magnitude of experimental excitation functions for a range of targets irradiated with protons of energies ranging from 0.8 to 3 BeV. Monte Carlo calculations of nuclear evaporation (Dostrovsky, Rabinowitz, and Bivins⁽³¹⁾) were modified by

Dostrovsky, Fraenkel, and Rabinowitz⁽³²⁾ to include the emission of ^6He , ^6Li , ^7Li , ^8Li , and ^7Be from Cu, Ag, Au, and Bi targets. (The incident protons were .34 to 2.0 BeV in energy.) The comparison with experimental results showed good agreement in most cases. Dostrovsky et al. attributed the fact that the calculated cross-sections were larger than the experimental values to an over-estimation of the interaction radius in the calculation of inverse cross-section and Coulomb barrier. Dostrovsky, Fraenkel, and Hudis⁽³³⁾ further modified the Monte Carlo procedure to obtain better statistical accuracy for the calculation of the formation cross-section of ^{13}N . They also recalculated the formation cross-sections for the emission of ^6He , ^8Li , and ^7Be using three different formulations of the interaction radius. The smallest value of the interaction radius was found to yield the best fit of calculated with experimental cross-sections. Dostrovsky, Davis, Poskanzer, and Reeder⁽¹⁰⁾ tested the predictions of evaporation theory for the emission of ^9Li , ^{16}C , and ^{17}N . Targets ranging from boron to uranium were irradiated with protons of 1.0 and 2.8 BeV energy. They calculated relative cross-sections assuming that fragments are evaporated from excited knock-on cascade products; the effect of secondary evaporation from excited evaporated fragments was also included. (Absolute cross-sections for the evaporation of complex particles can only be calculated if there is information available for the energies and spins of all relevant states of the particle and its possible progenitors.) Experimental and calculated cross-sections agreed well with

respect to their dependence on the mass number and the neutron-to-proton ratio of the target.

There have been numerous studies of the emission of fragments ${}^8\text{Li}$, ${}^8\text{B}$, and ${}^9\text{Li}$ in the high-energy-induced disintegrations of Ag and Br nuclei in emulsion.⁽³⁴⁻³⁷⁾ Experimental data of yield, energy, and angular distribution were found consistent with evaporation theory on the assumption that fragments are evaporated isotropically from the excited nucleus, which is moving in the direction of the incident particle with some mean velocity. A single value for this velocity, a single value for the nuclear temperature and a value for the Coulomb barrier were all chosen to fit the experimental data. However, the temperature was found to correspond to an excitation energy greater than the total binding energy of the nucleus while the Coulomb barrier value was much lower than expected. Because the high temperature did not seem reasonable the general conclusion was that either the evaporation mechanism is not valid or the calculation requires further refinement.

A detailed cascade-evaporation calculation to predict angular and energy distributions was done by Katcoff, Baker, and Porile⁽¹⁸⁾ for the emission of ${}^8\text{Li}$ fragments from Cu, Ag, and Au irradiated with protons of 2-BeV energy. The distribution of excited nuclei from the cascade process with regard to atomic number, mass number, and excitation energy was obtained from the calculation by Metropolis et al.⁽³⁸⁾ while the momentum imparted to the residual nucleus was obtained from Porile's extension to the Metropolis calculation.⁽³⁹⁾ A Monte Carlo

evaporation calculation was then done for fragments evaporated from the residual nuclei obtained from the cascade calculation. The motion of the emitting nuclei was included in the calculation. The calculated and experimental energy distributions agreed at the peak energies but the shape of the distributions differed at the low and high-energy ends of the spectra. The calculation under-estimated the probability of emission of high-energy (energy $>$ peak) fragments but successfully predicted their high forward-to-backward ratio. For low-energy fragments (energy $\leq$ peak) the calculated emission was larger than the experimental value for copper, in good agreement for silver, and smaller than the experimental value for gold. The forward-to-backward ratio of the low-energy fragments was nearly a factor of two larger than the calculated value. Cross-section calculations were approximate but matched the observed trend of cross-section with mass number. Because of the failure of the calculation to match the strong forward peaking of the angular distribution and its inability to account for the emission of the high-energy fragments, Katcoff, Baker, and Porile concluded that 'either a substantial fraction of the fragments is emitted by a process other than evaporation, or the emission is by a mechanism intermediate between evaporation and fast fragmentation'. Fragmentation*, a mechanism in addition to

*Fragmentation, as used in this thesis is in the sense proposed by Wolfgang et al.⁽⁴⁰⁾, rather than that suggested by Kruger and Sugarman⁽⁴¹⁾.

cascade and evaporation, is described below (2.i).

2. Fragment Emission a Fast Process

A fast reaction occurs in the time required for the incident particle to traverse the nucleus ($\sim 10^{-22}$ sec.). The incident particle reacts with only part of the nucleus and the emitted particle will take up an essential part of the momentum of the incident particle giving rise to typical angular distributions.

(i) 'Fragmentation' - π Mesons as Vehicle for Energy Transfer:

The mechanism termed 'fragmentation' was postulated by Wolfgang et al.⁽⁴⁰⁾ They noted that fragment production increases sharply at energies above 400 MeV while at these energies the production of π mesons in nucleon-nucleon collisions becomes significant. They postulated that fragmentation is associated with the short mean-free path of pions in nuclear matter which causes local heating due to pion absorption and can thus lead to the dissociation of the nucleus into fragments in a time short compared to that required for the equipartition of energy.

Baker and Katcoff⁽⁴²⁾ studied the interactions of protons of energies 1, 2, and 3 BeV with Ag and Br in emulsion and concluded that light fragments were formed both from evaporation and a fast process. They explained their angular distribution results in terms of inelastic collisions between incident protons and surface nucleons, the resulting pion being absorbed in the immediate vicinity and part of its energy

transferred to a newly-formed aggregate of nucleons.

Blau and Oliver⁽⁴³⁾ studied the interaction of pions of 750-MeV energy with emulsion nuclei and found evidence that fragment emission is accompanied by pion absorption.

Yasin⁽⁴⁴⁾ observed the emission of helium nuclei and tritons in the high-energy disintegration of Ag and Br nuclei. He calculated that a maximum of 19 alpha-clusters in the skin of the Ag and Br nuclei would explain the particle emission at energies greater than 50 MeV through absorption of pions in the alpha clusters. He suggested that for fragment emission, pion absorption takes place in a heavier nuclear cluster.

There has also been evidence that meson effects do not play a significant role in fragment production. For example, Crespo, Alexander, and Hyde⁽⁴⁵⁾ studied the emission of large fragments (^{24}Na and ^{28}Mg) from targets irradiated by both protons and alpha particles in the energy range 320 to 880 MeV. They found that the cascade initiated by alpha particles was similar to that initiated by protons of the same energy. They concluded that it was unlikely that mesons were produced in nearly the same intensity by helium ions as by protons.

Cumming, Cross, Hudis, and Poskanzer⁽⁴⁶⁾ measured the angular distribution of ^{24}Na nuclei produced by the bombardment of thin bismuth targets with protons of 2.9 BeV. They analysed the angular distribution and range data and found no moving system for which both angular distribution and velocity spectra were symmetrical about a direction perpendicular to the beam. They concluded that their results could not be described in

terms of a nucleonic cascade followed by a slow de-excitation step but rather in terms of fast fragmentation. However, they agreed with Crespo et al.⁽⁴⁵⁾ that Wolfgang et al.⁽⁴⁰⁾ may have over-emphasized the role of mesons in the fragmentation process.

Another mechanism proposed to explain fragment emission as a fast process is:

(ii) Quasi-Elastic Scattering of
Nucleons on Nucleon Clusters:

The existence of alpha-clusters at the nuclear surface was proposed by Hodgson⁽⁴⁷⁾ to explain the angular distribution of energetic alpha-particles produced in the irradiation of Ag and Br nuclei with 45-MeV protons. He was able to reproduce the experimental results by assuming direct alpha-particle knock-out with the existence of approximately 15 surface alpha-clusters.

The study of deuterons emitted from light nuclei bombarded with 675-MeV protons indicated that the protons were scattered by quasi-deuteron groups within the nucleus.⁽⁴⁸⁾ Blokhintsev⁽⁴⁹⁾ performed a quantitative calculation to show that 'supra-barrier' deuterons are produced by direct collision of an incoming nucleon with a tight nucleon cluster that results from fluctuations in the density of nuclear matter.

Theoretically the Brueckner model⁽⁵⁰⁾ of strongly correlated particles allows for nucleon clustering at low densities of nuclear matter, i.e. at the surface. On the evidence of alpha-decay and the relative frequency of the different modes of K-meson capture in the 'nuclear stratosphere',

Wilkinson⁽⁵¹⁾ postulated that nucleons near the surface are fleetingly clustered. Other evidence of the existence of nucleon clusters, principally as alpha-structures, has been given by Abate et al.⁽⁵²⁾ for the study of reactions caused by protons of 300-MeV energy incident on carbon, and by Gauvin et al.⁽⁵³⁾ for high-energy protons incident on bismuth. Furthermore light nuclei have been represented satisfactorily in terms of a cluster model.⁽⁵⁴⁾

Ostroumov and co-workers⁽⁵⁵⁾ explained their results for alpha-particles of energy greater than 30 MeV, emitted in the disintegration of nuclei induced by 100-600 MeV protons, in terms of collisions between nucleons and alpha-substructures at the nuclear surface. They noticed that for the same energies of bombarding protons, many of the characteristics of fast alpha-particle emission and fragment emission were similar.⁽²⁰⁾ In particular, the angular distribution of alpha-particles with energy ≥ 30 MeV was found identical to that of fragments with energy ≥ 1 or 2 MeV per nucleon. They concluded that fragment emission could also be explained in terms of nucleon collisions with nuclear clusters.

Although this mechanism was first proposed to explain fragment emission at high energies, a more interesting use has been to explain the angular distribution of fragment emission at low energies. Arifkhanov and co-workers⁽¹²⁾ studied the angular distribution of fragments produced by 100-MeV protons incident on photo-emulsion nuclei. On the basis of the highly asymmetric angular distribution (forward-to-backward ratio = 9.0) they

calculated the contribution of fragments from evaporation to be about 20%. To test the hypothesis that the remaining fragments were emitted as a result of quasi-elastic interactions of incident nucleons with nucleon clusters, they searched for and found a correlation between the emitted fragments and the fast recoil protons. According to formulas for elastic collisions for the interaction of 30-60 MeV protons with nuclei of mass 7 and 9, they were able to predict the dependence of fragment energy on emission angle. They reasoned that the fragments are knocked out by secondary nucleons produced in the nuclear cascade.

Makarov⁽¹⁶⁾ extended the study of fragment angular distribution to include incident protons of energy from 75 to 350 MeV. Again the asymmetry of the angular distribution (see Table I) was interpreted as due to the quasi-elastic ejection of fragments on the assumption of the existence of instantaneous substructures in the nucleus. Makarov⁽⁵⁶⁾ performed a calculation based on the cascade model with allowance for various groupings inside the nucleus, assuming some probability for their production, and a momentum distribution for each grouping within the nucleus. The calculation could not be carried out completely because of the lack of data for the differential scattering cross-sections for all the particles taking place in the cascade. (In order to predict α -particle emission, Abate et al.⁽³²⁾ performed Monte Carlo cascade calculations with allowance for quasi-alpha substructures using the known differential cross-sections for (p, α) reactions. Their results were in better

agreement with experiment than calculations assuming a pure nucleon-nucleon cascade.) However, the calculation was able to predict kinematic relations such as the energy spectra of particles emitted at a certain angle and the relation between the energy and emission angle of the scattered particles. A comparison of the calculated and experimental results indicated that, for incident protons of less than 100 MeV, fragments are knocked out of the nucleus by collisions with primary nucleons; for incident protons of energy greater than 100 MeV the fragments are produced by collisions with secondary nucleons. The decrease in asymmetry with energy is also attributed to this process.

Lefort, Cohen, Dubost, and Tarrago⁽⁵⁷⁾ found evidence for nucleons clustering into alpha-substructures. They studied the angular and energy distribution of complex particles emitted in nuclear reactions induced by 157-MeV protons on the heavy nuclei Ag, Au, Bi, and Th. Both an isotropic and a forward-peaked emission of alpha-particles, tritons, and deuterons were observed. Yields of ^3He -particles were, however, very low at the backward angles. The isotropic distribution was attributed to an evaporation mechanism. The forward-peaked emission was interpreted in terms of a direct interaction mechanism on alpha-clusters in the nuclear surface. Monte Carlo calculations were performed to compute the yield of alpha-clusters knocked out by prompt cascade nucleons. Clustering probabilities were chosen to give the best agreement of computed with experimental data. Lefort et al. suggested that the emission of tritons and

^3He -particles might be explained partly in terms of a double pick-up process and partly in terms of a stripping mechanism on alpha-clusters.

The success of the picture of fragment emission as being due to nucleon collisions is not complete. A knowledge of the relevant differential cross-sections is required to determine fully the applicability of this mechanism.

C. PURPOSE OF THE PRESENT STUDY

There has been little radiochemical investigation of fragment emission induced by low-energy protons. We have chosen to study the variation of the ^7Be formation cross-section with target mass for 85-MeV incident protons. The process of fragment emission is simplified at this energy as the nuclear cascade is not well developed and meson production is rare. As a detailed test for the mechanism of evaporation, the dependence of cross-section on the neutron-to-proton ratio of the target was investigated in a restricted mass region.

II. EXPERIMENTAL AND RESULTS

A. GENERAL CONSIDERATIONS

The probability of the formation of ^7Be in interactions of most nuclei with 85-MeV protons is low. Because of the difficulty of working with low activities, it was necessary to estimate the expected magnitude of ^7Be formation cross-sections for various targets to determine the required experimental conditions. The trend of magnitudes of expected cross-section, shown in Table II, was obtained by extrapolating the high energy (> 150 MeV) results of other workers back to 85 MeV.

TABLE II

TREND OF CROSS-SECTION MAGNITUDE WITH TARGET MASS

<u>Target</u>	<u>Order of Magnitude</u> Expected Cross-Section (mb)
O	8.0
Al	0.8
Cu	0.05
Ag	0.01
Au	0.001

In the present work, nuclei were chosen to span the nuclear mass range from oxygen ($A = 16$) to uranium ($A = 238$) with special interest in nuclei with masses from 48 to 65. For this mass region and incident particle energy, fragment emission is not obscured by spallation while the expected cross-sections

indicate reasonable counting rates. Target nuclei are listed in Table III.

TABLE III
TARGET CHARACTERISTICS

Target	Isotopes Present		Thickness mg/cm ²	Impurity %
	A	Abundance %		
O (CuO)	16	99.76	58*	Ni .0002; Fe .0001
Al	27	100	22.01	Ag .001; Cu .001; Fe .001; Mg .001
Ti	46	7.93	8.06	Cu .001; Fe .001; Mn .001
	47	7.28		
	48	73.94		
	49	5.51		
	50	5.34		
V	51	99.76	30.16	Cu .01; Fe .001
Fe	54	5.82	39.93	Cu .001; Ni .001; In .001; Mn .01
	56	91.66		
	57	2.19		
	58	0.33		
Co	59	100	58.09	
Ni	58	67.88	41.77	Co .1; Cu .01; Fe .01; Mg .1; Mn .1
	60	26.23		
Cu	63	69.09	45.37	Ag .001; Fe .001; Ni .0001
	65	30.91		
Cu	63	99.9	67.17	Al .02; Fe .03; Ni .01; Sr .02
	65	0.1		
Ag	107	51.35	55.20	Cu 0.1; Fe .001; Mg .001; Pb .01
	109	48.65		
Au	197	100	106.80	Ag .1; Cu .1; Fe .001; Ni .001; Pb .01; Pt .001
U	238	99.27	51.19	-

* Approximate thickness estimated for CuO powder.

Contamination of the target material by medium and heavy elements, determined by spectroscopic analysis*, is negligible as is shown in Table III. However, a spectroscopic analysis does not detect the presence of many light elements. Contamination by light elements, which have a relatively high ^7Be formation cross-section, may lead to false cross-section values, especially for the heavier targets. The oxygen layer on metal foils is a particular problem. All foils were cleaned to remove this layer and the targets were stored in an oxygen-free environment until irradiation. To detect the presence of gross light-element contamination, the difference in the shape of the excitation functions of light and heavier nuclei was exploited. Oxygen, a representative light element, was irradiated at proton energies from 30 to 85 MeV. The resultant excitation function is shown in Fig. 1. For our purposes the significant portion of the function is its negative slope from 65 to 85 MeV. The excitation function of ^7Be from a heavier element, aluminum, shown in Fig. 2, was constructed using our two cross-section values and the values of other workers. In this case the slope of the function is positive from 65 to 85 MeV. Previous high-energy results show that the cross-section for formation of ^7Be from targets heavier than aluminum always increases with energy up to the BeV region while the slope of the curve increases with increasing target mass. As a test for oxygen (and other light element contamination), all targets

*The author is indebted to Brookhaven National Laboratory for these analyses.

Figure 1

EXCITATION FUNCTION FOR THE PRODUCTION OF ^7Be
IN THE PROTON BOMBARDMENT OF OXYGEN

○ Present Data

■ Rayudu (58)

▲ Lignonniere et al. (59)

Figure 2

EXCITATION FUNCTION FOR THE PRODUCTION OF ^7Be
IN THE PROTON BOMBARDMENT OF ALUMINUM

- Present Data
- ▲ Benioff⁽⁶⁰⁾
- Friedlander, Hudis, and Wolfgang⁽⁶¹⁾
- Gray⁽⁶²⁾
- ⊙ Baker, Friedlander, and Hudis⁽⁴⁾
- △ Ligonniere, Vassent, and Bernas⁽⁵⁹⁾
- ▼ Lindsay and Neuzil⁽²⁷⁾
- Furukawa, Kume, and Ogawa⁽²⁹⁾

were irradiated at 65 as well as at 85 MeV. If the resultant excitation functions in this energy region are plotted for all the targets, the slopes of the functions are expected to increase with increasing target mass. It was anticipated that any deviations from this trend would indicate gross oxygen contamination. The presence of oxygen in the target would increase the cross-section value at 65 MeV relative to the value at 85 MeV.

B. TARGETS

All target nuclei with the exception of oxygen were irradiated as foils. The reaction $^{27}\text{Al}(p, 3p_n)^{24}\text{Na}$ was employed to monitor the proton beam and the cross-section values given in Cumming's review⁽⁶³⁾ were used as standards.

The enriched copper (99.9% ^{63}Cu) was obtained from Oak Ridge National Laboratory.

The target assembly consisted of three foils of aluminum (5.44 mg/cm^2 each) and three foils of the target element ($x \text{ mg/cm}^2$ each). Thus the target foil and the monitor foil were both sandwiched between guard foils which served to minimize ^7Be loss by recoil from the target and to eliminate ^7Be gain by recoil from the aluminum foil. The monitor guard foils were used to avoid ^{24}Na recoil loss.

Generally the target was irradiated downstream from the monitor foil. For several irradiations an additional monitor (with guard foils) was placed downstream from the target foil but no difference was observed in the activity of the

'forward' and 'backward' monitor foils.

The foils were stacked, clamped, and carefully cut to ensure alignment, especially at the leading edge. The distribution of activity from the leading edge was determined and accordingly after irradiation the first 1/8 in. of the leading edge was cut off and used. This portion, which was retained for use, contained 96% of the foil activity. The variation in foil area presented to the beam was found to be of the order of 1%.

On the basis of the activity distribution, ^7Be recoil loss from the leading edge was calculated to be less than 0.5%.

The thickness, x , of the target was chosen by imposing two limiting conditions, one tending to minimize x , the other to maximize it:

(i) Beam Degradation: x was chosen so that the energy

degradation of the beam was less than the energy spread of the McGill Synchrocyclotron (± 2 MeV). The degradation of 85-MeV protons in various materials was estimated using the data of Aron et al.⁽⁶⁴⁾

(ii) Recoil Loss of ^7Be : x was also chosen so that the

target was thick enough to minimize loss of ^7Be from the foil surface. To estimate the recoil loss from the total target assembly (target plus guard foils), an approximation of the Sugarman, Campos, and Wielgoz⁽⁶⁵⁾ expression was used:

$$2W(F + B) = R \quad (5)$$

where $W = 3x$ = thickness of target foil stack.

F = recoil loss in the forward direction (with respect to the beam).

B = recoil loss in the backward direction.

R = range of recoil fragment.

To calculate the range of ${}^7\text{Be}$ in various target materials, it was assumed that the ${}^7\text{Be}$ fragments were emitted with energy equal to the Coulomb barrier. The range-energy curves of Hower⁽²⁶⁾ for ${}^9\text{Be}$ in Al and Au were used to get approximate values for ${}^7\text{Be}$. It was always possible to choose 'W' so that the recoil loss from the target stack was less than 5% while satisfying the first condition. Hence the recoil loss from the target foil itself was negligible. Foil thicknesses used are given in Table III.

Oxygen was irradiated as CuO powder wrapped in gold foil. The 'specpure' CuO was obtained from Johnson, Mathey and Co. Ltd. Impurities are listed in Table III as detected by spectrographic analysis. To correct for ${}^7\text{Be}$ produced from copper and gold, blank irradiations of Cu powder in gold foil were performed at 70 and 85 MeV. The reaction ${}^{65}\text{Cu}(p, pn){}^{64}\text{Cu}$ was employed to monitor the beam and Meadows' cross-section values, as corrected by Meghir⁽⁶⁶⁾, were used as standards.

C. IRRADIATIONS

Irradiations were performed using the internal beam of the McGill Synchrocyclotron. To produce observable amounts of ${}^7\text{Be}$ the irradiation time for each target was estimated on

the basis of the expected cross-section and the beam intensity of approximately 5×10^{12} protons/sec. Bombardments were of one-half hour duration to two hours. The energy of the incident protons was obtained from a known radius-energy relation.⁽⁶⁷⁾

D. CHEMICAL SEPARATIONS

1. Beryllium

The target was dissolved in a suitable acid and a known amount of beryllium carrier (about 15 mg.) was added.

The targets Al, Fe, U, and CuO were dissolved in concentrated HCl; Ti was dissolved in dilute HCl; V and Ni were dissolved in dilute HNO₃; Cu, Ag, and Co were dissolved in concentrated HNO₃; Au was dissolved in aqua regia.

Separation methods given by Baker, Friedlander, and Hudis⁽⁴⁾ were used to purify ⁷Be from other radioactive nuclides.

The major contaminating activity in aluminum targets is ²²Na. Its 511-keV annihilation γ -ray interferes with the measurement of the 477-keV γ -ray of ⁷Be. Beryllium and aluminum were separated from sodium by precipitation of beryllium and aluminum hydroxides with ammonia. Aluminum was precipitated as AlCl₃·6H₂O by addition of ether and HCl (gas). Beryllium was then purified by extracting basic beryllium acetate with chloroform. The chloroform was evaporated, the residue dissolved in acid, and Be(OH)₂ was precipitated with a slight excess of ammonia.

The separation from all other targets (CuO, Ti, V, Fe, Ni, Co, Cu, Ag, Au, and U) was essentially the same. $\text{Be}(\text{OH})_2$ was precipitated a number of times with ammonia. The final precipitate was dissolved in concentrated hydrochloric acid and the solution was passed through a Dowex-1X-10 ion-exchange column. $\text{Be}(\text{OH})_2$ was again precipitated and dissolved, then a ferric hydroxide scavenging precipitation with NaOH performed. Beryllium ethylene-diamine-tetracetic acid complex was extracted with acetylacetone at pH 4-5 into benzene. Beryllium was back-extracted with 6N HCl and $\text{Be}(\text{OH})_2$ was precipitated after evaporation steps with nitric acid.

If the ^7Be sample was not radiochemically pure, separation steps were repeated.

Beryllium in its final form $\text{Be}(\text{OH})_2$ was dissolved in a minimum of acid and made up to a known volume with water. The volume varied from 2-5 ml. depending on the activity produced. In general, a 2 ml. aliquot was taken for activity measurements and the rest of the solution used for chemical yield determination. Where activities were low, the total beryllium samples were measured and the chemical yields determined later.

The chemical yields of beryllium were determined by the spectrophotometric method described by Sandell⁽⁶⁸⁾ using the complexing agent p-nitrobenzeneazo-orcinol. A standard curve is shown in Fig. 3. The chemical yields varied from 20-80%.

Figure 3

STANDARD ABSORBANCE CURVE FOR
BERYLLIUM SOLUTIONS

33a

2. Sodium

Chemical separation of sodium from the aluminum monitor foils was not necessary. Because of the short half-lives of other radioactive nuclides likely to be produced in the bombardment, no interfering activity is present if ^{24}Na ($t_{1/2} = 15$ hrs.) is measured 24 hours after bombardment. The aluminum was dissolved in acid, made up to a known volume (5 or 10 ml.) with water, and a 2 ml. aliquot taken for activity measurement.

3. Copper

It was necessary to separate the copper monitor from the CuO targets. After $\text{Be}(\text{OH})_2$ precipitation, $\text{Cu}(\text{OH})_2$ was precipitated from the solution, dissolved in concentrated HCl and evaporated to a small volume. The copper was then purified by absorption on a Dowex-1X-10 column with 4.5M HCl and elution from the column with 1.5M HCl . The copper was made up to a 5 ml. volume with water and a 2 ml. aliquot was taken for activity measurement.

The chemical yields of the copper were determined by titration with the disodium salt of ethylenediamine tetra-acetic acid using a murexide indicator.⁽⁶⁹⁾ The yields varied from 50-60%.

E. ACTIVITY MEASUREMENTS

The activity of all samples was obtained by γ -ray scintillation spectrometry.

To ensure reproducible sources, the 2 ml. aliquots

were contained in standard screw-cap vials of thin glass (15.5 mm x 50 mm).

1. ^7Be

^7Be decays by K-capture to ^7Li with 10.32% of the decays going to the 477-keV state and the remainder to the ground state.⁽⁷⁰⁾ The decay is characterized by a 53.6 day half-life. The internal conversion coefficient is negligibly small ($\alpha_K = 5.8 \times 10^{-7}$).

As a high detection efficiency was required, the activity of ^7Be samples was measured using a $1\frac{3}{4}'' \times 2''$ NaI(Tl) crystal with a centre well $\frac{5}{8}''$ in diameter and $1\frac{1}{2}''$ deep. The well crystal (Harshaw Chemical Company) was coupled to a photomultiplier tube (Dumont type 6292); photomultiplier pulses were fed via a cathode follower (RIDL model 31-15) into an amplifier and single channel pulse-height analyser (RIDL model 33-13A). The base line and window width, 82 keV, of the analyser were set to accept pulses about the 477-keV photopeak.

A standard ^7Be source was prepared by irradiating beryllium foil with 50-MeV protons. The standard source was used to calibrate the well counter and to check its day-to-day stability. The absolute gamma activity of the standard source was obtained in two ways: (i) The activity of the source was measured by a $3'' \times 3''$ NaI crystal coupled to a 100-channel pulse-height analyser. The assembly had been calibrated to yield the detection efficiencies for gamma rays of various energies by Grant, May, and Rayudu⁽⁷¹⁾ who had calibrated the

counter for standard gamma sources against a 4π -beta proportional counter. The 100-channel assembly consisted of a 3" x 3" NaI(Tl) crystal (Harshaw Chemical Company) coupled to a photomultiplier tube (Dumont type 6364), cathode follower (Hammer Electronics, model N-351), amplifier (Baird Atomic, model 215) and 100-channel pulse-height analyser (Computing Devices of Canada Limited, model AEP 2230). (ii) The absolute gamma activity of a standard ^7Be source was determined by Dr. Dallas Santry* of the Chalk River Nuclear Laboratory of Atomic Energy of Canada Limited. The two independent measurements agreed within 5%. The detection efficiency of the well counter and single channel assembly was found to be 16.2%.

The background counting rate of the counter was about 14.5 counts per minute. Samples with net count rates as low as 2 counts per minute could be measured with reasonable accuracy.

The purity of ^7Be samples was indicated by the 53.6 day half-life found. The decay was followed for at least seven half-lives. The gamma activity of sufficiently active samples was checked on the 100-channel analyser and the resultant spectra compared to that of the standard ^7Be source.

2. ^{24}Na

The 1.368-MeV γ -ray of ^{24}Na was detected and measured by the 100-channel analyser assembly. The area of the photo-peak was estimated by adding the individual counts in each

*The author is indebted to Dr. Santry for performing the measurement.

channel under it and the background under the peak subtracted in the same way as by the group⁽⁷¹⁾ who standardized the instrument. Because the 1.28-MeV γ -ray of ^{22}Na (a positron emitter) is too close to the 1.368-MeV γ -ray to be resolved from the latter, its contribution was determined by measuring the sample after the decay of the ^{24}Na was complete. The presence of ^{22}Na also increases the 'coincidence summing' effect. To minimize this effect, ^{24}Na sources were measured at a low geometrical efficiency.

3. ^{64}Cu

A γ - γ coincidence counter (Cosmic Radiation Laboratory, model 801) was used to measure the 511-keV annihilation γ -radiation of ^{64}Cu . The copper samples were placed within a copper tube to ensure the complete absorption of positrons in a given volume. The resulting annihilation quanta were detected by two $1\frac{1}{2}'' \times 1''$ NaI(Tl) crystals, placed at 180° to the source and coupled to single-channel pulse-height analysers (by means of the usual photomultiplier tube, cathode follower, and amplifier). The analysers, gated on the 511-keV photopeak were connected to the coincidence unit. Thus a pulse was recorded only when 511-keV γ -rays were detected by both counters in coincidence. To correct for accidental coincidences due to nuclear γ -rays, one of the detectors was paired with a third $1\frac{1}{2}'' \times 1''$ NaI(Tl) crystal placed at 90° to the source.

The γ - γ coincidence unit was calibrated against a 4π β -counter using ^{22}Na . (The ^{22}Na standard was measured in the

same position and under the same conditions as the ^{64}Cu samples.) The detection efficiency of the assembly was checked with a ^{22}Na standard source every time a positron measurement was made.

F. CROSS-SECTIONS

The gamma activity at the end of bombardment, A^0 , was obtained by extrapolating the decay curves back to zero time. The disintegration rate at the end of bombardment, D^0 , was then obtained from the equation:

$$D^0 = \frac{A^0}{E} \cdot \frac{1 + \alpha_T}{R} \cdot \frac{1}{Y} \cdot \frac{1}{F} \quad (6)$$

where E = efficiency of the counter.

α_T = total internal conversion coefficient.

R = branching ratio.

Y = chemical yield.

F = dilution factor.

As the target and monitor presented the same area to the beam, and as the energy degradation of the beam was negligible, cross sections for ^7Be formation were calculated from the equation:

$$\sigma_{^7\text{Be}} = \sigma_M \cdot \frac{N_M}{N_T} \cdot \frac{D_{^7\text{Be}}^0}{D_M^0} \cdot \frac{(1 - e^{-\lambda_M t})}{(1 - e^{-\lambda_{^7\text{Be}} t})} \quad (7)$$

The subscripts T and M refer to the target and monitor respectively, and

σ = cross-section.

λ = decay constant.

t = time of bombardment.

N = number of nuclei presented to the beam.

The ratio of nuclei presented to the beam may be found from the relation:

$$\frac{N_M}{N_T} = \frac{a_M \cdot b_M \cdot c_M}{a_T \cdot b_T \cdot c_T} \quad (8)$$

where a = natural abundance.

b = atomic weight.

c = superficial density in mg/cm^2 .

G. ERRORS

Errors involved in the cross-section determinations may be classified as systematic and random.

1. Systematic Errors

Systematic errors are associated with monitor cross-sections, detection efficiencies, branching ratios, internal conversion coefficients, and half-life values:

The limit quoted by Cumming⁽⁶³⁾ for the reaction $^{27}\text{Al}(p, 3pn)^{24}\text{Na}$ cross-section is $\pm 6.5\%$ while the limit quoted by Meghir⁽⁶⁶⁾ for the reaction $^{65}\text{Cu}(p, pn)^{64}\text{Cu}$ is $\pm 14\%$.

An error of $\pm 5\%$ was quoted by Grant⁽⁷¹⁾ for the determination of the detection efficiency of the $3'' \times 3''$ crystal. An error of $\pm 5\%$ was also assessed for the detection efficiency of the well crystal. (As previously mentioned, the

detection efficiency of the well crystal for 477-keV γ -rays was determined by two independent measurements of the absolute gamma activity of a ^7Be standard. One measurement was made with the 3" x 3" crystal. The error quoted by Dr. Santry for the second measurement was $\pm 3\%$. The two measurements agreed within 5%.)

Taylor and Merritt⁽⁷⁰⁾ cite an error of $\pm 1\%$ for their value of the branching ratio of ^7Be . The errors in the branching ratio values for ^{24}Na and ^{64}Cu have been given as $\pm 1\%$ ⁽⁷¹⁾ and $\pm 2\%$ ⁽⁷²⁾ respectively.

The magnitude of other systematic errors was negligible.

2. Random Errors

Random errors are connected with light element contamination, gamma activity determinations, chemical yields, foil thickness measurements, alignment accuracy and dilution factors:

The error associated with light element contamination of the target is difficult to assess in most cases. In the following section it is seen that there is evidence of light element contamination of certain targets. The corresponding cross-section values for ^7Be production from these targets were corrected for ^7Be production from the light element contamination. In each case an estimate was made of the uncertainty associated with the measured cross-section value.

At least 10,000 counts were accumulated in each gamma

measurement so that statistical fluctuations in the count rate were reduced to $\pm 1\%$. The error in the determination of the area of the 1.368-MeV photopeak was estimated to be $\pm 6\%$. An error of $\pm 3\%$ was assigned to count rates determined by coincidence technique.⁽⁷³⁾

Chemical yields were determined in duplicate and sometimes in triplicate. They agreed within 3-5%.

The uncertainty in the determination of superficial density was $\pm 1\%$.

The variation in foil area presented to the beam was 1%.

The error associated with pipetting and diluting was $\pm 1\%$.

The total error was calculated by taking the square root of the sum of the individual errors cited above for both ^7Be and the monitor. The uncertainty in the measured cross-sections for ^7Be from oxygen was estimated to be $\pm 17\%$ (the monitor was copper). The lower limit of the uncertainty in the measured cross-sections for ^7Be from the other targets was estimated to be $\pm 13\%$ (the monitor was aluminum). The uncertainty associated with the cross-section values corrected for light element contamination is given in the following section.

The spread in bombarding energy was reported by the Foster Radiation Laboratory Group to be ± 2 MeV.

H. RESULTS

Table IV contains the results of the cross-section measurements. The ^7Be activity at the end of bombardment, A^0 , the disintegration rate at the end of bombardment, D^0 , and the resultant ^7Be cross-section, $\sigma_{^7\text{Be}}$, are listed for each target and relevant proton bombarding energy, E_p . The mean value of the cross-section, $\bar{\sigma}_{^7\text{Be}}$, is given if more than one cross-section value was obtained at a given energy; the deviation of cross-section values from the mean is also given. Duplicate measurements agreed within the limits estimated in Section G.

The presence of oxygen and/or light element contamination in the target was indicated by the comparison of the cross-section measurements at 65 and 85 MeV. The cross-section values are plotted as a function of energy in Fig. 4. For each target a straight line drawn through the points approximates the excitation function in the energy region. As previously discussed in Section B, the slope of the excitation function for ^7Be formation is expected to be a function of target mass. In Fig. 4, the slope of the $\text{O}(p, ^7\text{Be})$ excitation function is negative; the slope of the $\text{Al}(p, ^7\text{Be})$ excitation function is positive, while the slope of the excitation functions of ^7Be from V, Ni, Co, and Cu increase in steepness with increasing target mass. However, the slope of the $\text{Ti}(p, ^7\text{Be})$ excitation function is steeper than expected from the general trend, while the $\text{Ag}(p, ^7\text{Be})$ excitation function is much flatter than expected.

TABLE IV

CROSS-SECTIONS FOR THE PRODUCTION OF ^7Be IN TARGETS BOMBARDED WITH LOW-ENERGY PROTONS

Target	E_p MeV	A° counts/min	D° dis/min	σ_M				$\sigma_7\text{Be}$ mb	$\bar{\sigma}_7\text{Be}$ mb	$(\bar{\sigma}_7\text{Be})_c$ mb
				$^{27}\text{Al}(p, 3pn)$ mb	$^{24}\text{Na}(63)$	$^{65}\text{Cu}(p, pn)$ mb	$^{64}\text{Cu}(66)$			
O (CuO)	30	105	22,400			390		2.9		
	45	510	130,000			236		5.3		
	60	960	239,600			180		9.9		
	70	1,590	340,200*			160		9.5		
	85	1,180	267,600*			140		9.0		
Al	70	54	170,500	9.55				0.76		
	85	137	37,500	10.1				1.08	1.06 $^{+0.01}$	
	85	136	82,700	10.1				1.05		
Ti	65	34	13,600	9.2				0.074		
	85	228	67,800	10.1				0.245	0.25 $^{+0.01}$	0.18
	85	80	15,400	10.1				0.260		
V	65	186	44,600	9.2				0.061		
	85	17	26,000	10.1				0.155	0.147 $^{+0.007}$	
	85	30	38,800	10.1				0.140		
Fe	85	38	15,200	10.1				0.108		
Co	65	30	5,850	9.2				0.036		
	85	108	23,500	10.1				0.081	.089 $^{+0.008}$	
	85	115	23,500	10.1				0.098		

/Contd.

TABLE IV (Contd.)

Target	E_p MeV	A° counts/min	D° dis/min	σ_M				$\sigma_{7\text{Be}}$ mb	$\bar{\sigma}_{7\text{Be}}$ mb	$(\bar{\sigma}_{7\text{Be}})_c$ mb
				$^{27}\text{Al}(p, 3pn)$ mb	$^{24}\text{Na}(63)$ mb	$^{65}\text{Cu}(p, pn)$ mb	$^{64}\text{Cu}(66)$ mb			
Ni	65	78	13,100	9.2				0.039		
	85	91	25,000	10.1				0.089	.095 $^{+}$.01	
	85	101	23,700	10.1				0.101		
^{63}Cu	65	80	16,400	9.2				0.019		
	85	94	18,200	10.1				0.064	.065 $^{+}$.01	
	85	38	11,550	10.1				0.066		
Cu	65	23	4,650	9.2				0.023		
	85	56	19,300	10.1				0.054	.068 $^{+}$.014	
	85	75	16,100	10.1				0.069		
	85	31	12,700	10.1				0.081		
$^{65}\text{Cu}^{**}$	85							0.074		
Ag	65	12	3,360	9.2				0.024		
	85	77	9,360	10.1				0.032	.028 $^{+}$.004	.0067
	85	36	4,250	10.1				0.025		
	85	31	6,450	10.1				0.027		

/Contd.

TABLE IV (Contd.)

Target	E_p MeV	A^0 counts/min	D^0 dis/min	σ_M		$\sigma_{7\text{Be}}$ mb	$\bar{\sigma}_{7\text{Be}}$ mb	$(\bar{\sigma}_{7\text{Be}})_c$ mb
				$^{27}\text{Al}(p, 3pn)$ mb	$^{24}\text{Na}(63)$ mb			
Au	65	14	1,710	9.2		0.0031		
	85	4	2,780	10.1		0.0045	.0035 $\pm$.001	~.0008
	85	16	3,490	10.1		0.0026		
U	65	160	22,100	9.2		0.021		
	85	222	18,100	10.1		0.013	.02 $\pm$.007	
	85	42	17,540	10.1		0.027		

* D^0 has been corrected for ^7Be produced from copper.

** Cross-section value was obtained by calculation using the experimental ^7Be cross-section values for ^{63}Cu and natural copper.

Figure 4

^7Be CROSS-SECTIONS PLOTTED AGAINST ENERGY OF THE
INCIDENT PROTON

Titanium is known to have a tenacious surface layer of oxygen. The observed ^7Be cross-section for the two irradiations at 85 MeV was higher than expected. Therefore for the irradiation at 65 MeV the surface of the target was cleaned after as well as before irradiation. To obtain a corrected cross-section value at 85 MeV, denoted $(\bar{\sigma}_{^7\text{Be}})_c$, the cross-section value at 65 MeV was then extrapolated to 85 MeV using a straight line of the same slope as the $V(p, ^7\text{Be})$ excitation function. The error associated with the corrected cross-section value was estimated to be $\pm 40\%$.

In the case of the $\text{Ag}(p, ^7\text{Be})$ reaction, the measurements at 65 and 85 MeV were made under the same conditions. The similarity of the two results definitely indicates light element contamination in the silver target. It was assumed that at 65 MeV the measured ^7Be was produced mainly from the light elements. The amount of ^7Be produced from light elements at 85 MeV was calculated by extrapolating the measured cross-section value at 65 MeV to 85 MeV using a straight line with the same slope as the $O(p, ^7\text{Be})$ excitation function; this cross-section value was then subtracted from the observed cross-section to yield an estimate of the ^7Be cross-section from silver. The error associated with the corrected cross-section value was estimated to be $\pm 100\%$.

The same procedure was used to obtain a very rough estimate of the ^7Be cross-section from gold. The error associated with the corrected cross-section value was estimated to be $\pm 300\%$.

It was not possible to obtain even an estimate of the cross-section value for uranium because of the low ^7Be production and the high contamination of the target.

The variation of the ^7Be formation cross-section with target mass number A is shown in Fig. 5 for bombarding protons of 85 MeV energy and in Fig. 6 for bombarding protons of 65 MeV energy. The uncertainty in the cross-section value is shown by the vertical bar. The curves follow the previously observed trend of ^7Be cross-section variation with mass number as shown in Fig. 7.

In Fig. 8, the ^7Be cross-sections are plotted against N/Z , the neutron-to-proton ratio of the target, for bombarding protons of 85 MeV energy.

Figure 5

CROSS-SECTION PLOTTED AGAINST MASS NUMBER, A,
FOR THE PRODUCTION OF
⁷Be IN TARGETS IRRADIATED WITH 85-MeV PROTONS

Figure 6

CROSS-SECTION PLOTTED AGAINST MASS NUMBER
FOR THE PRODUCTION OF
⁷Be IN TARGETS IRRADIATED WITH 65-MeV PROTONS

Figure 7

CROSS-SECTION PLOTTED AS A FUNCTION OF MASS
NUMBER FOR THE PRODUCTION OF ^7Be IN TARGETS
IRRADIATED WITH PROTONS HAVING A RANGE OF ENERGIES

The data for incident protons of 340 MeV energy
are from Baker, Friedlander, and Hudis⁽⁴⁾.

The data for incident protons of approximately
150 MeV energy are from Rayudu⁽⁵⁸⁾,
Ligonniere et al.⁽⁵⁹⁾ and Gray⁽⁶²⁾.

Figure 8

CROSS-SECTION PLOTTED AGAINST THE NEUTRON-TO-PROTON
RATIO OF THE TARGET FOR THE PRODUCTION OF
⁷Be IN TARGETS IRRADIATED WITH 85-MeV PROTONS

III. DISCUSSION

In view of the success of cascade-evaporation calculations in predicting cross-sections for high-energy fragment emission and the variation of these cross-sections with energy, target mass, and neutron-to-proton ratio of the target, it was thought profitable to attempt calculations along these lines.

A. BASIS OF PRESENT EVAPORATION CALCULATIONS

According to evaporation theory (outlined in Section I, pp. 7-9), the cross-section for the emission of ${}^7\text{Be}$ from an excited nucleus is given by

$$\sigma_{7\text{Be}} = \sigma_F \cdot \frac{\Gamma_{7\text{Be}} + \Gamma_{7\text{Be}}^*}{\sum_j \Gamma_j} \quad (9)$$

where σ_F = formation cross-section of the excited nucleus.

Γ_j = emission width for particle j

$$= \frac{g_j m_j}{\pi^2 \hbar^2} \int \sigma^*(E_j) \cdot \frac{\omega(E_f)}{\omega(E_i)} \cdot E_j \cdot dE_j$$

g_j = number of spin states of particle j .

m_j = mass of particle j .

$\sigma^*(E_j)$ = cross-section for the inverse reaction.

E_j = kinetic energy of particle j .

$\omega(E_f), \omega(E_i)$ = level densities of the final and initial nuclei at their respective excitation energies.

$\Gamma_{7\text{Be}^*}$ refers to the excited state of ^7Be , 0.43 MeV above the ground level. (The production of excited states of heavy particles as well as the ground state must be considered.)

The important factors to be evaluated in the above equation are the inverse cross-section, $\sigma^*(E)$, and the level density, $\omega(E)$.

The starting point for evaporation calculations is the spectrum of excited nuclides left after the completion of the knock-on cascade.

The maximum energy available for the evaporation of ^7Be from a residual nucleus (i.e. the maximum kinetic energy of the outgoing ^7Be) may be approximated as⁽⁷⁴⁾:

$$R_{7\text{Be}} \sim E^* - Q_{7\text{Be}} - \delta_{7\text{Be}} \quad (10)$$

where E^* = excitation energy of residual nucleus.

$Q_{7\text{Be}}$ = separation energy of ^7Be from residual nucleus.

$\delta_{7\text{Be}}$ = nucleon pairing correction.

According to the sharp cut-off approximation, the minimum kinetic energy of a ^7Be particle is given by the effective Coulomb barrier, $k_{7\text{Be}} V_{7\text{Be}}$.

The difference between the maximum and minimum energy may be regarded as the energy available for a residual to evaporate a particle. The factor, $(R_{7\text{Be}} - k_{7\text{Be}} V_{7\text{Be}})$, was estimated for residual nuclei which were formed by specific types of cascades. Average excitation energies of residual

nuclei, calculated by Metropolis et al.⁽⁷⁵⁾ were used to give an average value of $R_{7\text{Be}}$. The factor $k_{7\text{Be}} V_{7\text{Be}}$ was calculated in the manner described in the following section, A.1.(i). The estimation was performed for 82-MeV protons incident on the targets Al, Cu, and U, and the results are shown in Table V.

Table V
AVERAGE ENERGY AVAILABLE FOR THE EVAPORATION OF ^7Be
FROM RESIDUAL NUCLEI FORMED BY SPECIFIC-TYPE CASCADES
(82-MeV incident protons)

<u>Type of Cascade</u>	<u>$(\bar{R}_{7\text{Be}} - k_{7\text{Be}} V_{7\text{Be}})$ in MeV</u>		
	<u>Al</u>	<u>Cu</u>	<u>U</u>
Compound Nucleus Formation	49.8	49.4	40.5
p,n	0.7	10.2	7.2
p,p'	-0.5	3.4	-4.6
p,2n	-2.7	-1.2	-10.6
p,pn	-12.0	-11.6	-22.8
p,2p	-14.6	-14.4	

As seen in Table V, it is unlikely that ^7Be will be evaporated from nuclei which have been formed with the ejection of cascade particles. To simplify the present calculation, it is assumed that ^7Be is evaporated solely after compound nucleus formation.

1. $\sigma^*(E)$ - Inverse Cross-Section

Inverse cross-sections refer to excited states. It is not possible to determine experimentally the cross-sections for particles incident on highly excited nuclei. The inverse cross-section is therefore assumed equal to the total reaction cross-section for particles incident upon a nucleus in its ground state although there is no assurance that the size, shape, and barrier penetrabilities of an excited state are the same as the ground state. However, Ericson⁽⁷⁶⁾ points out that, if the cross-section is estimated on the basis of a completely absorbing square-well potential, the calculation is more valid for the excited than for the unexcited nucleus. He reasons that 'Nuclei in their ground state exhibit a rather strong transparency in nuclear reactions. This transparency is largely due to the exclusion principle which suppresses many otherwise possible scatterings of the incident particle, and seems to be largely connected with the specially ordered character of nuclear ground states. Qualitatively we therefore expect an excited nucleus to be 'blacker' than in the ground state; the exclusion principle is of less importance due to the increased diffuseness of the nuclear surface in momentum space.'

(1) Inverse Reaction Cross-Sections for Charged Particles:

In order to simplify the calculation of emission width, inverse cross-sections for charged particles are usually

represented in terms of calculated square-well cross-sections by the well-known sharp cut-off expression. The variation of cross-section with energy and atomic number is approximated:

$$\sigma^*(E_j) = \begin{cases} 0 & \text{for } E_j < k_j V_j \\ \pi R^2 (1 + c_j) (1 - k_j V_j / E_j) & \text{for } E_j > k_j V_j \end{cases} \quad (11)$$

where c_j and k_j are parameters that are functions of atomic number, Z , and V_j is the Coulomb barrier.

Dostrovsky, Fraenkel, and Friedlander⁽⁷⁴⁾ determined the values of the parameters c_j and k_j for protons, alphas, ^3H and ^3He particles by the best fit of equation (11) to tabulated continuum theory cross-sections of Shapiro⁽⁷⁷⁾ and Blatt and Weisskopf.⁽²²⁾ The classical barrier, V , was calculated by the formula:

$$V = \frac{z Z e^2}{R} \quad (12)$$

where z, Z = atomic number of outgoing particle and residual nucleus respectively.

e = electron charge.

$R = r_0 A^{1/3} + \rho$ = interaction radius between nucleus and charged particle; r_0 was set equal to 1.5×10^{-13} cm and ρ was taken equal to zero for protons and equal to 1.2×10^{-13} for all other emitted particles; A = mass number of residual nucleus.

No calculations have been performed to evaluate the dependence of the reaction cross-section of ^7Be on energy and

atomic number. Therefore the parameters $c_{7\text{Be}}$ and $k_{7\text{Be}}$ were determined in the following way:

Experimentally the reaction of 85-MeV protons incident on various targets was studied. The reaction is represented as $p(A, {}^7\text{Be})B$. ${}^7\text{Be}$ was emitted with kinetic energies ranging from $k_{7\text{Be}} V_{7\text{Be}}$ [the energy required to overcome the Coulomb barrier] to $R_{7\text{Be}}$ [the maximum kinetic energy of emission given in equation (10)]. The computer programme of D.R. Sachdev* was used to evaluate the reaction cross-section of ${}^7\text{Be}$ incident on various targets, B, with energy ranging from $k_{7\text{Be}} V_{7\text{Be}}$ to $R_{7\text{Be}}$. The calculation followed the outline described by T.D. Thomas⁽⁷⁸⁾ for the square-well potential model. Thomas found reasonable agreement with experiment for the radius parameter $r_0 = 1.5 \times 10^{-13}$ cm, hence this value was used. The computation was performed by an IBM 7040. For each target the reaction cross-section of ${}^7\text{Be}$ was evaluated at 1 MeV intervals between the energy limits. In Fig. 9 the calculated cross-section of ${}^7\text{Be}$ is plotted as a function of energy for ${}^7\text{Be}$ particles incident on ${}^{42}_{19}\text{K}$. As is shown in the figure a good fit to the curve was obtained using equation (11) with $(1 + c_{7\text{Be}}) = 0.974$ and $k_{7\text{Be}} = 0.983$. The classical barrier was calculated using equation (12) with $\rho = 2.43 \times 10^{-13}$ cm.⁽⁷⁹⁾ The calculated cross-section curve was fitted with equation (11) for each case of interest; the resultant values of $1 + c_{7\text{Be}}$ and $k_{7\text{Be}}$ are listed in Table VI and plotted as a

* The author is indebted to Mr. D.R. Sachdev for the use of his computer programme.

Figure 9

⁷Be REACTION CROSS-SECTION PLOTTED AGAINST ENERGY

0 - Cross-section computed according to outline described by T.D. Thomas⁽⁷⁸⁾ for the square-well potential model.

$$X - \sigma = \pi R^2 (1 + c_{7\text{Be}}) (1 - k_{7\text{Be}} \frac{V_{7\text{Be}}}{E_{7\text{Be}}})$$

Table VI
PARAMETERS IN EQUATION (11) FOR ^7Be CROSS-SECTIONS

A	Z	$1 + c_{7\text{Be}}$	$k_{7\text{Be}}$
—	—	—	—
21	10	1.013	.949
42	19	.974	.983
45	20	.988	1.018
53	24	.977	1.015
52	25	.975	1.018
54	25	.977	1.030
57	26	.975	1.024
59	26	.973	1.023
101	44	.940	1.046
103	44	.940	1.046
191	76	.898	1.046
232	89	.875	1.043

function of atomic number, Z, in Fig. 10. In every instance a good fit to the calculated curve was obtained and the fit was always remarkably good in the low-energy region where the sharp cut-off approximation is the weakest.

(11) Inverse Reaction Cross-Sections for Neutrons:

Dostrovsky et al.⁽⁷⁴⁾ approximated the dependence of neutron capture cross-sections as given by continuum theory⁽²²⁾ by the following equation:

Figure 10

PARAMETERS IN EQUATION (11) FOR ${}^7\text{Be}$ CROSS-SECTIONS
PLOTTED AGAINST ATOMIC NUMBER, Z

$$+ - 1 + c_{{}_7\text{Be}}$$

$$0 - k_{{}_7\text{Be}}$$

R_{7Bc}
OR
 $1 + C_{7Bc}$

$$\sigma^*(E_n) = \alpha(1 + \beta/E_n)\pi R^2 \quad (13)$$

where $\alpha = 0.76 + 2.2 A^{-1/3}$.

$$\beta = (2.12 A^{-2/3} - .050)/(0.76 + 2.2 A^{-1/3}) \text{ MeV.}$$

2. $\omega(E)$ - Level Density

Level densities possess well-known properties that have been explained in terms of various nuclear models. The outstanding property is the extremely rapid increase of level density with excitation energy. There is a noticeable difference in the level densities of odd and even nuclei. There is also an indication at low energies that level densities are influenced by nuclear shell structure.

We have chosen to use a level density formulation based on the Fermi-gas model^(80,81);

$$\omega(E) = C E^{-2} \exp[2(aE)^{1/2}] \quad (14)$$

where C = constant.

E = excitation energy.

a = level density parameter.

Because the odd-even effect seems mainly to cause a shift in the effective excitation energy between odd and even nuclei, this effect is taken into consideration by displacing the energy by an amount δ :⁽⁸²⁾

$$\omega(E) = C (E - \delta)^{-2} \exp[2\{a(E - \delta)\}^{1/2}] \quad (15)$$

where $\delta = 0$ for odd-odd nuclei and $\delta > 0$ for all other types.

The magnitude of the shift has been found close to the displacement in ground state energy caused by nuclear pairing, hence δ is usually taken to be the pairing energies for neutrons and protons. Cameron's⁽⁸³⁾ tabulation of pairing energies for even values of Z and N has been used in the present calculations.

The level density parameter, a , is frequently assumed proportional to the mass number, A ⁽⁸⁰⁾:

$$a = A/10 \quad (16)$$

where $1/10$ is a commonly-used constant of proportionality.⁽³¹⁾

In order to explain the effect of shell structure on level densities observed at the neutron binding energy, Newton⁽⁸⁴⁾ retained the assumption that level density is given by the Fermi-gas form, but introduced the level density parameter as

$$a = K (\bar{J}_n + \bar{J}_p + 1) A^{2/3} \quad (17)$$

where $\bar{J}_n$ and $\bar{J}_p$ are mean values of the spins of the neutron and proton shell model states which correspond to a particular $A = N + Z$. The values of $\bar{J}_n$ and $\bar{J}_p$ are obtained from Klinkenberg's⁽⁸⁵⁾ shell-model scheme based on a study of nuclei in or near their ground states. Newton evaluated the constant K by a least squares fit to the measured level densities at the neutron binding energy. Lang⁽⁸¹⁾ re-evaluated K on the basis of further low-energy experimental data to obtain:

$$a = 0.0748(\bar{J}_n + \bar{J}_p + 1)A^{2/3} \quad (18)$$

The influence of shell effects is expected to disappear with increasing excitation energy, but it is not known up to what energies shell effects are important.

Two values of the level density parameter have been used in the present calculation: $a = A/10$ and $a = 0.0748(\bar{J}_n + \bar{J}_p + 1)A^{2/3}$.

The experimental results have been examined in terms of evaporation theory with the above assumptions, both in a qualitative and quantitative manner.

B. QUALITATIVE ACCOUNT OF VARIATION OF ^7Be CROSS-SECTION WITH TARGET ELEMENT

The variation of cross-section with target element may be accounted for in an approximate manner following the method of Hower: (26)

^7Be is assumed to be evaporated solely from the compound nucleus and the simple formulation of the level density, $\omega(E) = C \exp[2\{a(E - \delta)\}^{1/2}]$, (23,82) is used. The cross-section for ^7Be formation may then be written:

$$\sigma_{^7\text{Be}} \sim$$

$$\frac{\sigma_{\text{CN}} g_{^7\text{Be}} m_{^7\text{Be}} \int \sigma^*(E_{^7\text{Be}}) \exp[2\{a_{^7\text{Be}}(E - Q_{^7\text{Be}} - \delta_{^7\text{Be}} - E_{^7\text{Be}})\}^{1/2}] \cdot E_{^7\text{Be}} \cdot dE_{^7\text{Be}}}{\sum_j g_j m_j \int \sigma^*(E_j) \exp[2\{a_j(E - Q_j - \delta_j - E_j)\}^{1/2}] \cdot E_j \cdot dE_j} \quad (19)$$

where the numerator refers to ${}^7\text{Be}$ and the denominator summation is carried out over all particles emitted from the compound nucleus; σ_{CN} is the cross-section for the formation of the compound nucleus.

If the indicated integration of the level density term is carried out, the result is $f(E-Q-\delta -kV)\exp[2\{a(E-Q-\delta -kV)\}^{\frac{1}{2}}]$. It is assumed that only the exponential term is important in determining relative cross-sections.

It is further assumed that ${}^7\text{Be}$ emission competes with the emission of only one other particle, $\underline{b}$, which is the most likely particle evaporated from the compound nucleus. The cross-section for ${}^7\text{Be}$ formation is then:

$$\sigma_{7\text{Be}} \sim \text{constant} \frac{\exp[2\{a_{7\text{Be}}(R_{7\text{Be}} - k_{7\text{Be}}V_{7\text{Be}})\}^{\frac{1}{2}}]}{\exp[2\{a_b(R_b - k_bV_b)\}^{\frac{1}{2}}]} \quad (20)$$

where $R = E-Q-\delta$,

$$\text{or } \sigma_{7\text{Be}} \sim \text{constant} \exp(S_{7\text{Be}} - S_b) \quad (21)$$

where $S = 2\{a(R - kV)\}^{\frac{1}{2}}$.

According to equation (21), a plot of the log of the experimental cross-section, $\log \sigma_{7\text{Be}}$, versus the quantity $(S_{7\text{Be}} - S_b)$ should be a straight line.

In Fig. 11, $\log \sigma_{7\text{Be}}$ is plotted versus $(S_{7\text{Be}} - S_b)$ for the level density parameter $a = A/10$. The evaporated particle, $\underline{b}$, for which $(R_b - k_bV_b)$ was the largest, was used in the

Figure 11

CROSS-SECTIONS PLOTTED AGAINST $(S_{7_{\text{Be}}} - S_b)$ FOR
 $a = A/10$

● - Monoisotopic target

○ - Polyisotopic target

calculation. The log of the experimental cross-section was first plotted as a function of $(S_{7_{\text{Be}}} - S_b)$ for all monoisotopic targets. A straight line was drawn through the points in agreement with equation (21). On the assumption that the straight line relationship holds true for all isotopes, cross-sections for target elements which contained more than one isotope were corrected for isotopic abundance as follows: The quantity $(S_{7_{\text{Be}}} - S_b)$ was determined for all isotopes of a given target element which were present in amounts greater than 1%. The slope of the straight line drawn through the points for the monoisotopic targets was used to estimate the contribution to the total cross-section for each isotope of a polyisotopic target, relative to the contribution from the most abundant isotope. These relative contribution factors were used as weighting factors for the isotopic abundances. Finally, the observed cross-section of a polyisotopic target was divided by the sum of the adjusted percent abundances of the isotopes present. The adjusted cross-sections were plotted as a function of $(S_{7_{\text{Be}}} - S_b)$ for the most abundant isotope along with points for monoisotopic targets, and the locus of the straight line was re-determined. The fit of the points to a straight line was satisfactory.

In Fig. 12, $\log \sigma_{7_{\text{Be}}}$ is plotted versus $(S_{7_{\text{Be}}} - S_b)$ for the level density parameter $a = 0.0748(\bar{J}_n + \bar{J}_p + 1)A^{2/3}$ for monoisotopic targets. For this value of the level density parameter, no relationship exists between $\log \sigma_{7_{\text{Be}}}$ and $(S_{7_{\text{Be}}} - S_b)$

Figure 12

CROSS-SECTIONS PLOTTED AGAINST $(s_{\text{Be}} - s_b)$ FOR

$$a = 0.0748(\bar{j}_n + \bar{j}_p + 1)^{2/3}$$

which indicates that shell effects play no role in level densities at 85 MeV.

C. QUANTITATIVE CALCULATION OF CROSS-SECTION
FOR ^7Be EMISSION

As previously stated, it is assumed that the evaporation of ^7Be does not occur from products of the prompt knock-on cascade.

Energy considerations suggest that ^7Be is most probably evaporated from the compound nucleus but may also be evaporated from the product nuclei formed by particle evaporation.

1. Cross-Section for the Formation of ^7Be
from the Compound Nucleus

The cross-section for the emission of ^7Be from the compound nucleus was calculated according to equation (9) with

$$\sigma_F = \sigma_R \cdot F_{\text{CN}} \quad (22)$$

where σ_R = proton-reaction cross-section.

F_{CN} = fraction of reaction which yields compound nucleus formation.

The proton-reaction cross-section was calculated using equation (11) with $r_0 = 1.5 \times 10^{-13}$ cm.

The fraction yielding compound nucleus formation was obtained from the results of the Monte Carlo calculations on intra-nuclear cascades of Metropolis et al. (75,86)

Emission width was computed by substituting the

inverse cross-section as given by equations (11) and (13) and the level density as given by equation (15) into equation (3):

$$\Gamma_j = \frac{g_j m_j}{\pi \hbar^2} r_o^2 A_j^{2/3} \cdot (E - \delta_o)^2 \exp[-2\{a_o(E - \delta_o)\}^{1/2}] C_j$$

$$\cdot \int_{k_j V_j}^{R_j} (E_j + \beta - k_j V_j) \exp[2\{a_j(E - Q_j - \delta_j - E_j)\}^{1/2}] (E - Q_j - \delta_j - E_j)^{-2} \cdot dE_j \quad (23)$$

where subscripts o and j refer to the original and residual nucleus respectively. For neutrons, C_j denotes α and $k_j = 0$; for protons, C_j denotes $(1 + c_j)$ and $\beta = 0$.

Because the integration of equation (23) in closed form is not possible, its integral was approximated by the summation:

$$\sum_{k_j V_j}^{R_j} (E_j + \beta - k_j V_j) \exp\{2[a_j(E - Q_j - \delta_j - E_j)]^{1/2}\} (E - Q_j - \delta_j - E_j)^{-2} \Delta E_j \quad (24)$$

The summation was performed by an IBM type 7040 computer for $\Delta E_j = 0.1$ MeV. Sample emission widths were calculated for values of ΔE_j ranging from 0.01 to 1.0 MeV. Emission width was plotted as a function of ΔE_j and the value of the emission width for $\Delta E_j = 0$ was determined by extrapolation. It was found that the emission width calculated for $\Delta E_j = 0.1$ MeV differed from the estimated emission width for $\Delta E_j = 0$ MeV by .001%. Smaller values of ΔE_j greatly increased

the computer time required to perform the summation.

Separation energies, Q , were computed on the basis of experimental atomic mass data compiled by König et al.⁽⁸⁷⁾ For nuclei for which experimental mass values were not available, masses computed from Levy's empirical mass formula⁽⁸⁸⁾ were used.

Emission width was determined for two values of the level density parameter. For $a = 0.0748(\bar{J}_n + \bar{J}_p + 1)A^{2/3}$, emission width was determined for neutrons, protons, deuterons, tritons, alphas, ^3He , ^7Be and $^7\text{Be}^*$ particles. The probability of ^7Be emission, $P_{^7\text{Be}} = \frac{\Gamma_{^7\text{Be}} + \Gamma_{^7\text{Be}^*}}{\sum_j \Gamma_j}$, was then calculated.

The inclusion of the emission width of tritons and ^3He particles to the sum $\sum_j \Gamma_j$ made little difference to the value obtained for $P_{^7\text{Be}}$. Hence for the level density parameter $a = A/10$, emission width determination was confined to neutrons, protons, deuterons, alphas, ^7Be and $^7\text{Be}^*$ particles.

The calculated quantities for the proton-reaction cross-section, σ_R , the fraction of compound nucleus formation, F_{CN} , the probability of ^7Be emission from the compound nucleus, $(P_{^7\text{Be}})^{\text{CN}}$, and the cross-section for ^7Be emission from the compound nucleus, $(\sigma_{^7\text{Be}})^{\text{CN}}$, are presented in Table VII.

For the level density parameter $a = 0.0748(\bar{J}_n + \bar{J}_p + 1)A^{2/3}$, calculated and experimental ^7Be cross-sections are plotted as a function of target mass number, A , in Fig. 13. As was seen in Section III B, this value of the level density parameter fails

Table VII

Target	σ_R mb	F_{CN}	$a = 0.00748(\bar{J}_n + \bar{J}_p + 1)A^{2/3}$		$a = A/10$			Exptl.
			$(P_{7Be})^{CN}$	$(\sigma_{7Be})^{CN}$	$(P_{7Be})^{CN}$	$(\sigma_{7Be})^{CN}$	σ_{7Be}	σ_{7Be}
				mb		mb	mb	mb
^{27}Al	862.8	.05	3.96×10^{-3}	0.17	3.32×10^{-3}	0.143	0.248	1.064
^{48}Ti	1069.0	.107	5.52×10^{-7}	0.63×10^{-4}	4.86×10^{-4}	0.056	0.073	
Natural Ti								0.182
^{51}V	1097.3	.115	2.6×10^{-6}	0.33×10^{-4}	3.62×10^{-4}	0.044	0.052	0.147
^{59}Co	1139.7	.133	1.25×10^{-3}	0.189	3.21×10^{-4}	0.044	0.056	0.089
^{58}Ni	1134.2	.131	8.16×10^{-3}	1.22	5.8×10^{-4}	0.087	0.104	
^{60}Ni	1139.8	.136	8.17×10^{-3}	1.26	6.1×10^{-4}	0.094	0.108	
Natural Ni				1.23		0.089	0.105	0.095
^{63}Cu	1166.3	.143	2.23×10^{-3}	0.37	4.41×10^{-4}	0.073	0.099	0.065
^{65}Cu	1169.2	.147	3.03×10^{-3}	0.52	2.05×10^{-4}	0.035	0.045	0.074
Natural Cu				0.42		0.062	0.082	0.068
^{107}Ag	1420.1	.23	1.22×10^{-7}	4.0×10^{-5}	2.13×10^{-5}	.0070	.0084	
^{109}Ag	1439.3	.233	2.67×10^{-7}	8.95×10^{-5}	0.69×10^{-5}	.0023	.0026	
Natural Ag				6.38×10^{-5}		.0047	.0066	.0067
^{197}Au	1696.0	.375	9.36×10^{-6}	5.95×10^{-3}	2.06×10^{-9}	1.3×10^{-6}		~.0008
^{238}U	1792.7	.45	1.085×10^{-11}	8.75×10^{-9}	3.77×10^{-10}	3.04×10^{-7}		-

Figure 13

CROSS-SECTIONS PLOTTED AGAINST MASS NUMBER, A

- - Experimental cross-section values
- - Calculated cross-sections for ${}^7\text{Be}$
formation from the compound nucleus,
 $(\sigma_{7\text{Be}})^{\text{CN}}$, for $a = 0.0748(\bar{J}_n + \bar{J}_p + 1)A^{2/3}$

CROSS-SECTION (mb.)

to predict the observed variation of cross-section for ${}^7\text{Be}$ formation with target element. There is no relation between calculation and experiment. The shell-effects observed at low energies and represented by the Newton-Lang formulation do not persist then to the excitation energies encountered here. This was predicted by Ericson⁽⁷⁶⁾ who cautioned about the use of the Newton formula for excitation energies much above neutron binding energies.

For the level density parameter $a = A/10$, calculated and experimental values of the ${}^7\text{Be}$ cross-section are plotted as a function of target mass number, A , in Fig. 14. As expected the calculation under-estimates the experimental cross-sections as only evaporation of ${}^7\text{Be}$ from the compound nucleus was considered.

2. Estimate of the Total Cross-Section for Formation of ${}^7\text{Be}$

The contribution to the ${}^7\text{Be}$ cross-section for ${}^7\text{Be}$ evaporated following particle emission was estimated in the following approximate manner:

In the first step of the evaporation chain, the compound nucleus de-excites by evaporating a particle of varying kinetic energy. The excitation energy of the product nucleus so formed is a function of this kinetic energy. The most probable kinetic energy, E_{mp} , of the evaporated particle has been given by Dostrovsky, Fraenkel, and Friedlander⁽⁷⁴⁾ as:

Figure 14

CROSS-SECTIONS PLOTTED AGAINST MASS NUMBER, A

0 - Experimental cross-section values

■ - Calculated cross-sections for ${}^7\text{Be}$
formation from the compound nucleus,

$$(\sigma_{7\text{Be}})^{\text{CN}}, \text{ for } a = A/10$$

$$E_{mp} = V + a_j^{-1} [(a_j R_j + 1/4)^{1/2} - 1/2] \quad (25)$$

where $V = k_j V_j$ for charged particles.

$V = -\beta$ for neutrons.

For each compound nucleus of interest, the most probable excitation energy of the product nuclei formed by neutron, proton, deuteron and alpha emission was thus determined. The probability of ${}^7\text{Be}$ emission from each product, $(P_{{}^7\text{Be}})^j$, at its most probable excitation energy, was calculated as in the preceding section (III.C.1).

The contribution from ${}^7\text{Be}$ emission further along the evaporation chain was assumed to be negligible on the basis of energy considerations.

The total ${}^7\text{Be}$ cross-section was then estimated to be:

$$\begin{aligned} \sigma_{{}^7\text{Be}} = & (\sigma_{{}^7\text{Be}})^{\text{CN}} + (P_n)^{\text{CN}} (P_{{}^7\text{Be}})^n + (P_p)^{\text{CN}} (P_{{}^7\text{Be}})^p \\ & + (P_d)^{\text{CN}} (P_{{}^7\text{Be}})^d + (P_\alpha)^{\text{CN}} (P_{{}^7\text{Be}})^\alpha \end{aligned} \quad (26)$$

The cross-section for ${}^7\text{Be}$ formation, $\sigma_{{}^7\text{Be}}$, was estimated according to equation (26) for the level density parameter $a = A/10$ and is given in Table VII.

In Fig. 15, calculated and experimental ${}^7\text{Be}$ cross-sections are plotted as a function of target mass number, A . With the exception of the light elements there is reasonable agreement between calculated and experimental values. However, the experimental points vary smoothly with A while the

Figure 15

CROSS-SECTION PLOTTED AGAINST MASS NUMBER, A

- - Experimental cross-section values
- - Calculated cross-sections for $a = A/10$

calculated points are scattered. Scatter of the experimental points may be masked by the experimental error. Dostrovsky et al.⁽¹⁰⁾ found that cross-sections for fragment production in irradiations with high-energy protons were a smoother function of the target neutron-to-proton ratio, N/Z , than the target mass, A . In the following section, experimental and calculated ^7Be cross-sections are plotted as a function of N/Z .

The calculation under-estimates the production of ^7Be from the light targets Al, Ti, and V. The under-estimation does not seem to be due to the fact that the contribution of ^7Be evaporation following knock-on cascade was neglected. Examination of Table V indicates that following the knock-on cascade more energy is available for ^7Be evaporation from irradiated Cu than Al. In Fig. 16, the difference between the calculated and experimental ^7Be cross-sections, $(\sigma_E - \sigma_C)$, is plotted against target mass number, A . Although the points are limited they fall on a straight line, indicating that a mechanism other than evaporation contributes to the formation of ^7Be in these targets.

D. VARIATION OF THE CROSS-SECTION FOR ^7Be EMISSION WITH THE NEUTRON-TO-PROTON RATIO OF THE TARGET

Calculated ($a = A/10$) and experimental values of the ^7Be cross-section are plotted as a function of target neutron-to-proton ratio, N/Z , in Fig. 17.

A straight line, I, may be drawn through the experimental points for the targets O, Al, Co, Cu, and Ag.

Figure 16

$(\sigma_E - \sigma_C)$ PLOTTED AGAINST MASS NUMBER, A

Figure 17

CROSS-SECTIONS PLOTTED AGAINST TARGET
NEUTRON-TO-PROTON RATIO, N/Z

- - Experimental cross-section values
- - Calculated cross-sections for $a = A/10$

I

II

Ni

Ti

v

$$N/Z$$

There is considerable scatter of the rest of the points about this line. Points for the neutron-rich targets Ti and V are above the line. [The most abundant isotopes of these elements (^{48}Ti (73.9%): $N/Z = 1.18$; ^{51}V (99.8%): $N/Z = 1.22$) have high neutron-to-proton ratios relative to the stable isotopes in the surrounding mass region.] The point for the neutron-poor Ni is substantially below the line. [The most abundant Ni isotopes (^{58}Ni (67.9%): $N/Z = 1.07$; ^{60}Ni (26.2%): $N/Z = 1.14$) have low neutron-to-proton ratios relative to stable isotopes in the same mass region.]

However, as was shown in Fig. 16, a mechanism other than evaporation contributes significantly to the production of ^7Be in the irradiated targets Al, Ti, and V, while spallation accounts for a large fraction of the production of ^7Be from O. A curve, II, may be drawn through the experimental points for the remaining targets as well as the calculated points.

As the present data are limited and include low cross-section values, previous low-energy data are plotted in the same manner in Figs. 18 and 19.

In Fig. 18, the points represent cross-section values of Lindsay and Carr⁽²⁴⁾ and Neuzil and Lindsay⁽²⁸⁾ for ^7Be emission in 40-MeV alpha-particle irradiations. If a straight line is drawn through the points, the cross-section value for Ti is again above the line and the value for Ni below the line. Alternately, two lines may be drawn through the points, which suggests one mechanism for the production of ^7Be from Mg, Al, and Ti and another mechanism for the production of ^7Be from

Figure 18

CROSS-SECTIONS PLOTTED AGAINST TARGET
NEUTRON-TO-PROTON RATIO, N/Z : ${}^7\text{Be}$ EMISSION
IN 40-MeV ALPHA-PARTICLE IRRADIATIONS

○ - Lindsay and Carr⁽²⁴⁾

■ - Neuzil and Lindsay⁽²⁸⁾

Ni, Co, Cu, and V targets. As mentioned in Section I.1.(i), there has been evidence that evaporation is not the sole mechanism for ^7Be production in light targets irradiated with low-energy alpha particles: Recoil studies by Porile⁽²⁵⁾ indicate that evaporation and some direct mechanism contribute approximately equally to the formation of ^7Be in Al irradiated with 40-MeV alpha-particles. The existence of the compound nucleus as a step in the formation of ^7Be was questioned by the fact that alpha-particle-induced cross-sections for the target Ti were found to be much greater (5 to 10 times) than the corresponding proton-induced cross-sections for V (Lindsay and Neuzil⁽²⁷⁾); similarly the alpha-induced cross-sections were found to be much greater than the corresponding proton-induced cross-sections for Al (Furukawa et al.⁽²⁹⁾; Lindsay and Neuzil⁽²⁷⁾). (However, the discrepancy can be explained in terms of the large amount of angular momentum a He ion can bring into the entrance channel.)

In Fig. 19, cross-section values for ^7Be formation are plotted as a function of N/Z for targets irradiated with 130-MeV protons (Rayudu⁽⁵⁸⁾) and 155-MeV protons (Ligonniere et al.⁽⁵⁹⁾). Again the results indicate the contribution of another mechanism for the production of ^7Be in light element targets.

The variation of ^7Be cross-section with target neutron-to-proton ratio seems to suggest that more than one mechanism is responsible for ^7Be formation. However, the data are too limited to be conclusive.

Figure 19

CROSS-SECTIONS PLOTTED AGAINST TARGET
NEUTRON-TO-PROTON RATIO, N/Z

○ - 130-MeV proton irradiation - Rayudu⁽⁵⁸⁾

■ - 155-MeV proton irradiation - Ligonniere et al.⁽⁵⁹⁾

As shown in Fig. 17, evaporation theory does predict the N/Z dependence of ${}^7\text{Be}$ cross-sections for medium mass targets ($A > 55$). According to evaporation theory, the dependence of cross-section on target neutron-to-proton ratio arises primarily from differences in the binding energies of ${}^7\text{Be}$ in the evaporating nuclei. The decrease in cross-section with target mass for the neutron-deficient fragment ${}^7\text{Be}$ may be partly attributed to the fact that, as the target mass increases, the neutron-to-proton ratio of the fragment becomes further removed from the neutron-to-proton ratio of the stability valley of the target region (the decrease in cross-section is also attributable to the increase in the factor $k_7 V_7$).

E. CONCLUDING REMARKS

The present work adds to the evidence that more than one mechanism contributes to fragment formation.

1. The Evaporation Mechanism

Evaporation as a mechanism for ${}^7\text{Be}$ emission from medium and heavy targets ($A > 55$) has here successfully predicted cross-section magnitudes and the variation of cross-section with the neutron-to-proton ratio of the target.

However, in evaporation theory, changes of parameter can result in large changes in cross-section magnitude. This is illustrated in Table VII by the difference in cross-section values predicted by the two level density parameters.

The dependence of the ${}^7\text{Be}$ cross-section on target N/Z

does not necessarily indicate an evaporation mechanism. (The N/Z dependence of cross-section for the light targets does not suggest an evaporation mechanism.) A possible process which possesses some of the qualitative features of the N/Z dependence was suggested by Dostrovsky et al.⁽¹⁰⁾: 'According to this mechanism a 'cold' fragment is splintered off the nucleus as a consequence of the nucleonic cascade. Qualitatively it will be seen that the composition of such a fragment will reflect that of the target nucleus, and therefore a neutron-rich nucleus will favour the production of neutron-excess fragments over that of neutron-deficient ones.'

The outstanding contradiction to evaporation theory in our energy range is the pronounced asymmetry of fragment angular distribution. Makarov⁽¹⁶⁾ has studied the angular distribution of fragments emitted in the disintegration of Ag and Br nuclei in emulsion. Incident protons varied from 76 to 350 MeV. If one plots the forward-to-backward ratios obtained by Makarov as a function of energy, the forward-to-backward ratio for 85-MeV protons is approximately 15. The marked peaking of fragments in the proton beam direction is inconsistent with a slow process but indicates a relation between fragment emission and a fast cascade process.

The time scale of the evaporation process does become short as the excitation energy increases. It is a basic assumption of the statistical model that the lifetime of the intermediate compound system must not be shorter than the nuclear relaxation time. Lifetimes and relaxation times are

expressed in terms of the passage time of a light signal through the nucleus: $2R/c = A^{-1/3} \times 10^{-23}$ sec (where R = nuclear radius, c = velocity of light, A = nuclear mass number). Using Ericson's equation⁽⁷⁶⁾, the lifetime for neutron emission, τ_n , may be estimated in units of $2R/c$ for a mass 64 nucleus at excitation energies of 20, 90 and 200 MeV:

Excitation Energy	τ_n
MeV	$2R/c$
20	14,500
90	58
200	7

Ericson estimates the lower limit for the relaxation time to be 5 or 10 times $2R/c$.

At 20 MeV, the lifetime of the excited nucleus is much greater than the relaxation time. At 90 MeV, the excitation energy of present concern, the lifetime of the excited nucleus is about 8 times the relaxation time. In this rather short lifetime, a particle must accumulate enough energy by random collisions to escape. At 200 MeV the lifetime of the excited nucleus is comparable to the relaxation time; there is no clear separation between fast and slow processes.

Ericson⁽⁷⁶⁾ points out that at excitation energies greater than 100 MeV, the agreement between evaporation calculations and experiment is surprisingly good considering the short-time scale of the evaporation process at these energies. He suggests that either the relaxation time is

shorter than estimated or the evaporation mechanism holds for incompletely equilibrated systems. He proposes that 'agreement between evaporation theory and experiments may rather be regarded as a pure phase space effect It is thus possible that we are here dealing with a case which indicates the usefulness of the Statistical Model regarded only as a phase space description. It may then have approximate validity outside its ordinary range of applicability'.

To explain the success of evaporation theory in predicting the variation of the cross-section for the formation of light fragments with target mass and composition for high-energy reactions, Dostrovsky et al.⁽¹⁰⁾ suggest 'that the production process involves the binding energies of the fragment to the parent nucleus and is therefore sensitive to the details of the mass-energy surface. The evaporation formalism includes the mass-energy surface in a natural manner. Indeed the agreement between the experimental cross-sections and the predicted relative yields strongly indicates that some aspects of the evaporation formalism (namely the mass-energy surface) is an important part of the description of the formation of light fragments'.

2. Contribution to Fragment Emission from a Direct Mechanism

Qualitatively the results can be explained in terms of two mechanisms, evaporation and a fast process.

The asymmetry of the fragment angular distribution

has suggested that fragments are produced by the direct process of the scattering of nucleons on nucleon clusters. The effect of collisions with clusters is expected to be more important in interactions with light nuclei where the cascade is likely to consist of one, two or three collisions. In heavy nuclei collisions with single nuclei are expected to dominate.

According to this picture, the contribution of evaporation to fragment production is expected to increase with target mass. This explains the decrease in fragment asymmetry with increase in target mass and, for the non-evaporation mechanism, the decrease in fragment production with target mass shown in Fig. 16.

IV. SUMMARY AND CONTRIBUTION TO KNOWLEDGE

The excitation function was determined for the production of ^7Be formed in oxygen irradiated with 30-85 MeV protons.

Cross-sections were measured for the production of ^7Be in targets irradiated with protons of 65- and 85-MeV energies. Targets were chosen to span the nuclear mass range from oxygen ($A=16$) to uranium ($A=238$) with special interest in nuclei with masses from 48 to 65.

The variation of the measured cross-sections with the mass and neutron-to-proton ratio of the target was observed.

The experimental results at 85 MeV were examined in terms of evaporation theory both in a qualitative and quantitative manner. Calculations were performed for two values of the level density parameter:

(1) $a = 0.0748 (\bar{J}_n + \bar{J}_p + 1)A^{2/3}$: No relation was found between calculation and experiment indicating that shell-effects play no role in level densities at 85 MeV.

(2) $a = A/10$: For the emission of ^7Be from medium and heavy targets ($A > 55$), the calculations were found to predict reasonably well cross-section magnitudes and the variation of cross-section with the mass and neutron-to-proton ratio of the target. The calculation underestimated the production of ^7Be from the light elements ($27 < A < 55$). This suggests that a mechanism other than evaporation contributes to the formation of ^7Be in these targets.

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