Systematics of Isotope Production with Radioactive Beams

C. H. Dasso,[1] G. Pollarolo,[2] and A. Winther[1]
[1]*The Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen Ø, Denmark*
[2]*Istituto Nazionale di Fisica Nucleare and Dipartimento di Fisica Teorica dell'Universitá, Torino, Italy*
(Received 13 May 1994)

Extending the field of spectroscopy to very neutron-rich heavy nuclei has been impaired by reaction Q values that consistently favor the formation of the lighter isotopes. Radioactive beams offer a chance to overcome this difficulty. We carry out a systematic study of cross sections for multinucleon transfer processes in order to determine the actual neutron excess in the projectiles that is needed to revert the aforementioned tendency. This identification, supplemented by quantitative predictions for the production yields, provide concrete guidelines for the selection of reaction partners and bombarding conditions.

PACS numbers: 25.60.+v

Several laboratories around the world are presently planning to either implement or expand their ability to handle projectiles farther away from the stability line [1–4]. These facilities open a new era of structure research, as a host of novel nuclear systems shall become available for spectroscopic studies. One interesting possibility is that of creating neutron-rich isotopes of heavy nuclei via multinucleon transfer processes. The actual possibilities to achieve this objective must, however, be carefully examined. One could naively think that any neutron excess in a light projectile has a fair chance to be deposited in a target. A simple glance at the nuclear chart of the known isotopes tells us otherwise. For charges above $Z \approx 60$ the vast majority of all isotopes produced by ordinary nuclear reactions are neutron poor.

This principle is embodied in a rule well known to reaction specialists, namely, that only proton stripping and neutron pickup are likely to occur in transfer processes involving stable projectiles. As a consequence, target nuclei tend to gain some charge while losing neutrons, a mechanism that populates systems to the "left" of the stability valley. The reason for this lies in characteristics of reaction Q values which one can visualize. In a collision process involving a light projectile and a heavy target the balance of Q values for the transitions to $Z \pm \Delta Z$, $N \pm \Delta N$ is mostly controlled by the lighter partner. Since the contours of binding energies in the NZ plane in the vicinity of the light stable nuclei are roughly symmetric around $N = Z$, it is clear that a cut for a given element ($Z =$ const) yields a steeper energy gain toward the lighter isotopes than toward the heavier, thus favoring the acquisition of neutrons.

As one takes heavier isotopes of a given projectile a transition toward the opposite situation should eventually take place. In this specific context there are then two important issues that need be addressed:

(a) What amount of neutron excess in the projectile is necessary to favor the production of neutron-rich isotopes of heavy nuclei?

(b) What is the actual isotope dependence of the yields as, for instance, given by the slope $\partial\sigma(Z_0 + \Delta Z, N_0 + \Delta N)/\partial\Delta N$? (In other words: What factor in cross section is "lost" every time one reaches out to the next, heavier isotope?)

In order to provide an answer to these questions we explore in this Letter multinucleon transfer processes for a wide range of situations spanning projectiles with charge $Z \leq 50$. To conduct this survey we exploit the model presented in Ref. [5]. This calculation scheme is simple enough to allow us to contemplate a systematic study of rather ambitious proportion while still retaining a capacity to make predictions of quantitative value. It is hoped that the considerations and results that follow will prove useful for the selection of projectiles, targets, and bombarding conditions in reactions with radioactive beams. We note, however, that we are concerned mostly with the formation rates of the different isotopes. The excitation energies at which the systems are generated—even at grazing collisions—and their short half-lives do not make them all equally available for spectroscopic studies. A study of these important complementary aspects of the problem is under way.

As a first step we investigate how the isotope production of heavy nuclei evolves as the projectile gradually acquires a larger neutron excess. Consider for instance the results shown in Fig. 1 for the specific case of the reaction ^{A}Ca + ^{120}Sn at 150 MeV. The figure displays contours of cross section for the multinucleon transfer processes where the projectile undergoes a net change in charge ΔZ_P and in neutron number ΔN_P. The frames correspond to three different isotopes of calcium with $A = 40, 48$, and 54. One can immediately notice the shifting character of the pattern, from one that favors neutron pickup and proton stripping (for ^{40}Ca) to one in which neutron stripping and proton pickup mostly take place (for ^{54}Ca). Somewhere between these two extremes there exists a situation, like the one shown in the center frame, where the production rate of nuclei around the target, i.e., the cross section

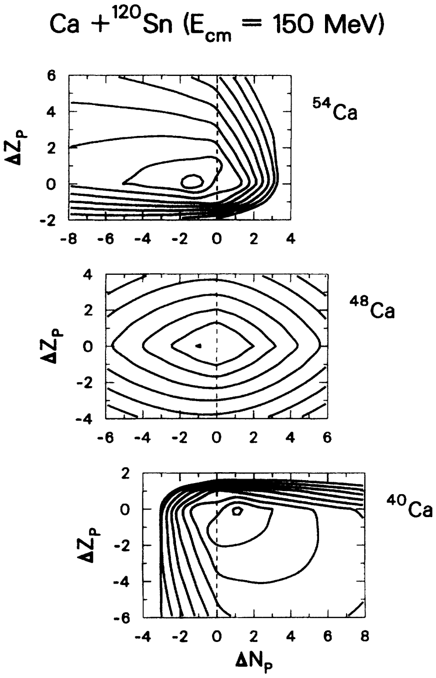

FIG. 1. Contours of differential cross sections as a function of the change in projectile neutron number ΔN_P and charge number ΔZ_P, for the reaction ^{A}Ca + ^{120}Sn. The calculations are for a center-of-mass bombarding energy of 150 MeV and the frames correspond, from the bottom to the top, to $A = 40$, 48, and 54. The contour values are arbitrary as the figure is meant to display the shifting character of the population patterns as the neutron excess in the projectile increases.

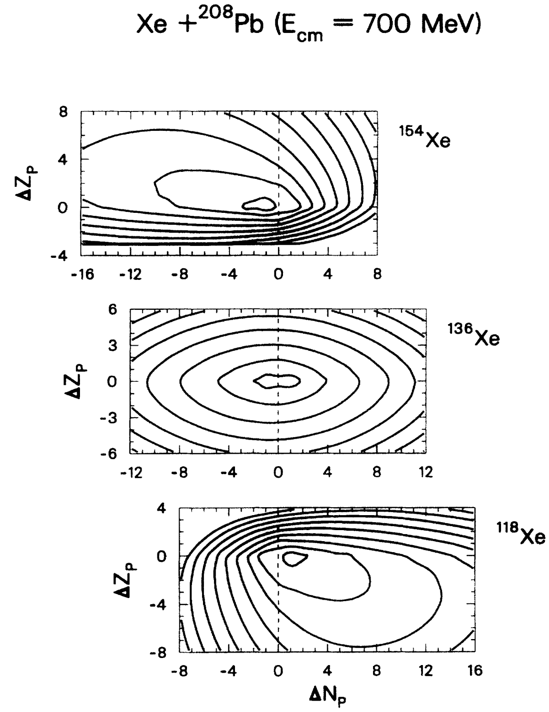

FIG. 2. Same information as in Fig. 1 but for a heavier projectile. Here, the case is ^{A}Xe + ^{208}Pb at a center-of-mass bombarding energy of 700 MeV.

gradient in both charge and number of neutrons, is uniformly distributed.

We have conducted similar calculations for a large variety of projectiles and targets and found that the characteristics of the results in Fig. 1 are common to all combinations involving a light projectile and a heavy target. There is no point in showing in this medium a collection of these cross-section contours. Let us just indicate that the term "light projectiles" can here be used for nuclei of rather high charge—up to about fifty—provided the targets are still substantially heavier (cf. Fig. 2 for ^{A}Xe + ^{208}Pb at 700 MeV).

This procedure, carried out systematically, makes it possible to identify the particular isotope of each element in the nuclear chart where the transition from one regime to the other occurs. Since stable projectiles (and those with a small neutron excess) are not suitable to generate heavy isotopes the line in the NZ plane connecting these points should lie to the right of the stability valley. The results of our survey indeed define a clear boundary, shown by the dashed line in Fig. 3. Taking a margin of an extra two neutrons to be on the safe side of the transition, we conclude that only projectiles chosen in the shaded area of the plot are appropriate for our stated purpose. Notice that the borderline goes precisely over ^{48}Ca, thus leaving no naturally existing nucleus on this zone. Actually, for most elements the shaded area is somewhere between five to seven neutrons away from the last stable isotope. Thus, the importance of the radioactive beam programs as a means of supplying possible candidates need not be emphasized.

Once a proper selection of the projectile has been made, it turns out that multinucleon transfer processes can in fact provide significant population for a substantial number of isotopes. This is illustrated in Fig. 4, where cross sections as a function of neutron number are collected for two different elements produced in the reaction ^{A}Xe + ^{208}Pb at 700 MeV. The frame to the left corresponds to the formation of polonium isotopes, and the three curves displayed are for $A = 118$, 136, and 154 (full, dashed, and dotted, respectively). Since $\Delta Z_P = -2$, the largest populations result in this case from the use of ^{118}Xe, i.e., the typical situation for stable projectiles. The right frame of the figure shows, instead, the production rates for the different isotopes of mercury ($\Delta Z_P = 2$) resulting from the same selection of xenon projectiles. Besides confirming the qualitative trends previously discussed this figure now provides a concrete idea on how far away from the stability line one can expect to explore the family of heavy isotopes for elements with charge slightly below Z_T.

One can immediately observe a systematic shift in the position of the maximum cross sections that directly

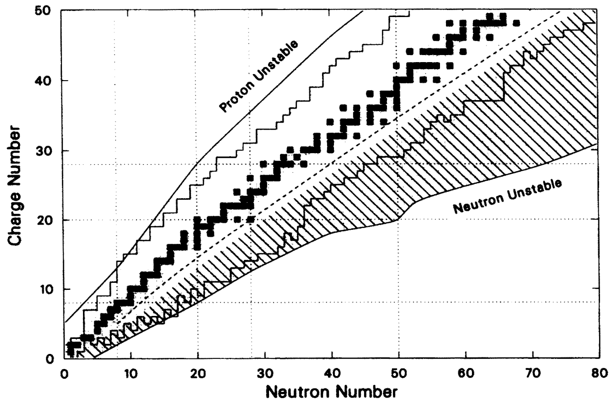

FIG. 3. The dashed line superimposed to the nuclear chart shows the location of the nuclei with charges up to $Z = 50$ that lead—when used as a projectile with a heavier target—to gradients for multinucleon transfer in both charge and mass that are evenly distributed. The shaded area (arbitrarily shifted by a couple of extra neutrons) thus indicates the range of projectiles that can be used to favor the production of neutron-rich heavy isotopes.

reflects the total neutron content in the different reactions. It is interesting to see that, on the heavy-isotope side, mercury formation rates by ^{154}Xe only drop by a decade with the addition of five neutrons. Rather flat slopes were also obtained for the other neutron-rich projectiles included in the present survey. These estimates are quite promising as they point to production rates that are considerably higher than previously expected. For instance, calculations for the production of plutonium isotopes reported in Ref. [6] carry, for a similar gain of five neutrons, an inhibition factor of $\approx 10^5$.

A qualitative understanding that one may transfer many neutrons with a relative small transition probability p_{ik} between two given single-particle states i and k is obtained by realizing that there is a large number of

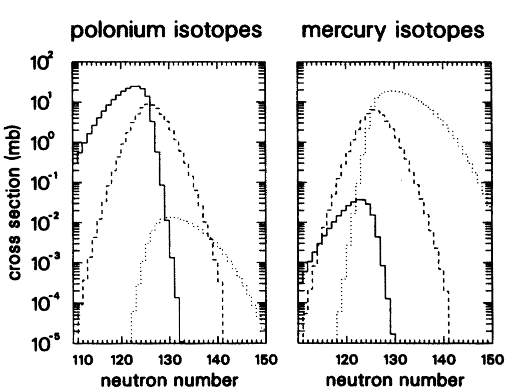

FIG. 4. Total cross sections for the production of different isotopes of polonium (left) and mercury (right) in the reaction ^{A}Xe + ^{208}Pb at 700 MeV bombarding energy. The full, dashed, and dotted histograms correspond, respectively, to $A = 118$, 136, and 154.

configurations available. The total drift of neutrons from the projectile can be estimated by

$$\sum_{ik} p_{ik} \approx \langle p \rangle \left(g_A \frac{\hbar}{\tau} \right) [g_a(Q_{gg} - Q_0)],$$

where the first factor is the average value of p_{ik}. The second factor is the number of states one may reach in the target from a given projectile state. This is the product of the level density in the target g_A times the width of the Q value window (i.e., $\hbar$ divided by the collision time). The third factor is the number of projectile states that may contribute; this is the product of the single-particle level density in the projectile times the height of the Fermi level in the projectile over the Fermi level in the target corrected by the optimum Q value Q_0. For the case in question g_a, $g_A \approx 10\ \text{MeV}^{-1}$, $\hbar/\tau \approx 4$ MeV, and $(Q_{gg} - Q_0) \approx 3$ MeV, and one can see that even with an average probability $\langle p \rangle \approx 10^{-2}$, drifts of the order of 10 can easily be obtained. The calculations of Fig. 4 are done with impact parameters leading to distances of closest approach larger than the sum of the nuclear radii. The main contribution to the largest neutron transfers ($\Delta N \approx 20$) comes from distances of closest approach only 0.5 fm outside this distance, and it is expected that a rather large fraction of the collisions corresponds to deep inelastic processes which may eventually lead to a similar mass partition. With similar arguments the main excitation energy of the recoil with $\Delta N = 20$ can be estimated at $\langle E^* \rangle \approx 20(Q_{gg} - Q_0) \approx 60$ MeV, with a spread $\sigma \approx \sqrt{20}\hbar/\tau \approx 20$ MeV. These rather high values confirm that neutron evaporation can cause, as anticipated, a major redistribution of the probability over the recoils.

To conclude, we give an impression on the variation in cross sections and range of isotope formation which results from changing the bombarding energy within the grazing regime. Total cross sections for the production of mercury and tallium isotopes in the reaction ^{54}Ca + ^{208}Pb are shown in Fig. 5. The different curves are for $E_{cm} =$ 180, 200, 220, and 240 MeV, that roughly correspond to the Coulomb barrier and 10%, 20%, and 30% above. The maximum cross sections around $N = 126$ are quite similar, given that the ratio of all energies within the span is close to unity. The extent of heavy isotope production for both elements shows, on the other hand, a much more appreciable dependence on the bombarding energy. To understand this behavior one can refer to the formula above. In fact, lowering the bombarding energy one increases the collision time and squeezes the Q value window, thus reducing the average number of transferred neutrons. The main effect is, however, associated with the fact that by increasing bombarding energy the grazing distance is decreased, thus leading to more intimate collisions in the grazing region.

We have given in this Letter an overview of the trends for isotope production via multiple transfer processes

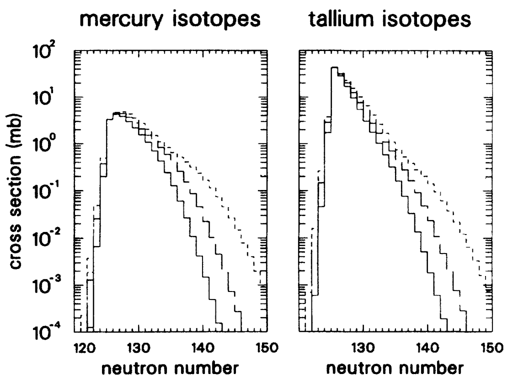

FIG. 5. Total cross sections for the production of different isotopes of mercury (left) and tallium (right) in the reaction $^{54}Ca + ^{208}Pb$ at four bombarding energies near the Coulomb barrier. The full, dash-dotted, dashed, and dotted histograms correspond, respectively, to $E = 180$, 200, 220, and 240 MeV.

revealed by a systematic sampling of neutron-rich projectiles that might soon become available in radioactive beam facilities. We conclude that only a considerable neutron excess is likely to overturn the normal tendency to produce nuclei that are lighter and a slightly more charged than the original target. We make a definite prediction for the location of the transition line in the NZ plane and also give quantitative estimates on the extent in mass number in which the isotopes are likely to be produced. The results are encouraging, insofar as they point to higher production rates than those hitherto assumed.

This work was supported in part by the Heraeus Foundation and the DFG Grant No. Bo 1109/1 and the EU Network Contract No. CHRX-CT92-0075.

[1] Holifield Heavy Ion Research Facility Proposal, edited by J. D. Garret and D. K. Olsen, 1991.

[2] Study Group, European Radioactive Beam Facilities, May 1993 (unpublished).

[3] ADRIA Proposal, Istituto Nazionale di Fisica Nulceare, Laboratori Nazionali di Legnaro (Pd), Italy, 1992.

[4] IsoSpin Laboratory Report No. LALP 91-51, prepared by North American Steering Committee for ISL.

[5] A. Winther, Fizika **22**, 41 (1990); Nucl. Phys. **A572**, 191 (1994).

[6] *Proceedings of the International Symposium on Structure and Reactions of Unstable Nuclei, Niigata, Japan,* edited by K. Ikeda and Y. Suzuki (World Scientific, Singapore, 1992).

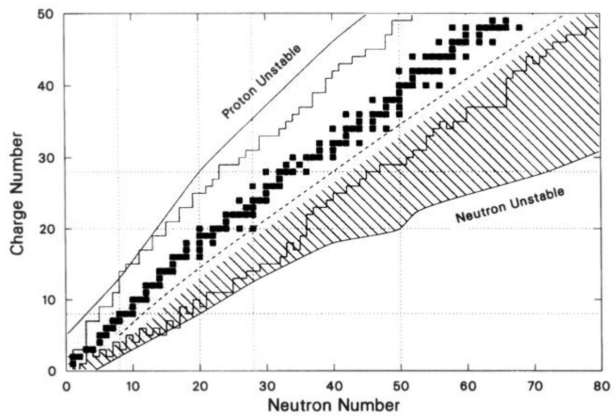

FIG. 3. The dashed line superimposed to the nuclear chart shows the location of the nuclei with charges up to $Z = 50$ that lead—when used as a projectile with a heavier target—to gradients for multinucleon transfer in both charge and mass that are evenly distributed. The shaded area (arbitrarily shifted by a couple of extra neutrons) thus indicates the range of projectiles that can be used to favor the production of neutron-rich heavy isotopes.