Production of A+1 and Z+1 isotopes in proton-induced reactions on ^{A}Z nuclei. Application to Po production in p-^{209}Bi and to Bi production in p-^{208}Pb reactions.

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Abstract. It is pointed out that the production of certain isotopes with mass and charge close to the target ones can be attributed to specific channels and sometimes to specific reaction mechanisms in terms of binary collisions. The most striking case is the production of A+1 isotopes, which can be obtained through (p,π) channels only. The contribution of pion-producing channels is also underlined for the production of Z+1 isotopes, although these channels are not exclusive in this case. The description of the production of all these isotopes can be considered as a good testing ground for intranuclear cascades concerning the treatment of the pionic degrees of freedom. Data for the proton-induced reactions on ^{208}Pb and ^{209}Bi are compared with the predictions of the recent version of the INCL4 model, which has especially been improved in the pion sector. Good agreement is generally obtained. It is however stressed that for A+1 isotopes, the agreement is obtained owing to the energy-dependence of the nucleon mean field and arguments are given to indicate why this energy-dependence shows up in these special reactions and not in most of the other observables. The production of the same isotopes in thick targets is also investigated.

1. Introduction

Most of the isotopes produced in spallation reactions induced by nucleons in the GeV range have a mass and a charge smaller than the original mass and charge of the target nucleus, respectively. This is consistent with the current model for these reactions, namely the intranuclear cascade+evaporation model. According to this model, most of the time, the incident nucleon expels a few energetic nucleons from the target nucleus, leaving the latter in a moderately excited state, which thereafter emits other (slow) nucleons by evaporation. However, occasionally, the mass of the so-called residue exceeds the target mass number, by one mass unit. This is possible when the incident nucleon is absorbed and a pion is emitted (at low energy, a photon replaces the pion).

Some other isotopes can be produced only with an accompanying pion in the final state. For instance, isotopes with two extra charges compared to the target one are produced only through (p,π^-) or ($p,xn\pi^-$) reactions.

Residues with a charge one unit larger than the target charge can be produced by conventional (p,xn) reactions (except when their mass number exceeds the target mass number by one unit, in which case a (p,π^0) process is at work).

This set of reactions are quite interesting, because they involve the emission of a single pion or of a pion with a very low number of nucleons. They are especially interesting because they correspond to well defined channels, as we already mentioned. In addition, if one considers, as in INC models, that the dynamics is dominated by collisions, the relevant reaction mechanisms can be identified almost unambiguously. For instance, the A+1 isotopes are produced in a single nucleon-nucleon (NN) inelastic scattering where the two nucleons do not receive enough energy to be emitted and where the pion leaves the nucleus without interaction[1]. These rather strong requirements makes this process rare infrequent. If there was another collision, the conditions for having a A+1 isotope would be even more drastic. The production of the $^{A}(Z+2)$ isotope is possible through the ($p,n\pi^-$) channel only. This

[1]One may consider pion production as due to an inelastic collision producing a Δ-resonance, followed by the decay of the latter. The conclusion is the same.

corresponds to a single inelastic scattering, where one of the nucleons does not receive enough energy to be emitted and where the other one and the pion can leave the nucleus while delivering to it a small excitation energy. If there was a second collision, the conditions for remaining in this channel would be much more drastic. The production of the $^{(A-1)}(Z+2)$ isotope is possible the (p,2nπ^-) channel only. This must correspond this time to at least two collisions: an inelastic one followed by an elastic one (or in the reverse order) with the proper conditions. Let us finally discuss the case of the Z+1 isotopes. The production of the $^{A}(Z+1)$ isotope can proceed to the (p,n) channel. This should correspond to a single elastic collision, leaving little excitation energy to the target. The production may also proceed through the (p,nπ^0) and (p,pπ^-) channels. This time this corresponds to a single-inelastic collision leading to low excitation energy. The production of the $^{(A-1)}(Z+1)$ isotopes correspond to the (p,2n), (p,2nπ^0) and (p,pnπ^-) channels and to mechanisms involving two collisions at least, with appropriate conditions and with various orderings. In summary, the production of isotopes close to the target allows identification with specific channels and simple reaction mechanisms. As one is moving from the target, the identification of channels is progressively more ambiguous and the reaction mechanisms (in terms of collisions) multiply and are less and less constrained.
These considerations show that the production of these special isotopes provides with a good test for dynamical models, especially for pion dynamics. We have recently [1] improved this feature in the INCL4 model [2], which has been shown to give, when coupled with the ABLA evaporation-fission code [3,4], a fairly good description of a large amount of data concerning proton-induced spallation reactions in the 200 MeV-2 GeV range[2,5]. In this paper, we want to apply our INCL4 model, modified according to Ref. [1], and test its predictions for residue production close to the target mass region in p-Pb and p-Bi collisions. Our work is also motivated by radio-protection problems posed by the development of Pb or Pb-Bi spallation sources, for which the production of Po may be a serious concern.

2. A brief description of the model.

We refer to Ref. [2] for a detailed description of the standard INCL4 model. It is sufficient here to remind that the INCL model is a time-like intranuclear cascade model tracking all the particles, which move in straight lines between collisions governed by a minimum distance of approach criterion. The nucleons experience a potential well, describing the nuclear mean field, and they suffer transmission or reflection on the surface of this well, according to their energy and transmission probabilities for plane waves on a potential step. Although classical in nature, the model incorporates some quantum aspects: Pauli blocking of collisions, quantum transmission through the nuclear surface, stochastic determination of the final states in NN collisions and existence of a mean field. Finally, we want to stress that the model does not include free parameters. There are, of course, parameters such as those characterizing the initial distribution or those entering the procedure for evaluation of the phase space occupancy, but they have been determined once for all. There is no adjustable parameter left to the user. Even the stopping time, i.e. the time at which the cascade process is stopped to give place to evaporation is determined self-consistently, as explained in Ref. [2].

Although the standard INCL4 model is quite successful [2], it has been improved on several points during the last years. We refer to Ref. [6] for a general discussion. The improved version used in this work brought modifications on three points: (i) the introduction of an isospin- and energy-dependent mean field for nucleons, as described in Ref. [1], (ii) the introduction of nuclear and Coulomb potentials for pions, as described in Ref. [1]; additional minor changes, also quoted in the same reference, deal with pion-nucleon cross sections and the mass of the Δ-resonances, (iii) a strict Pauli blocking is applied to the first collision. The utilized nucleon and pion mean fields are largely inspired by the phenomenology of the respective optical-potential models. Point (iii) requires some explanation. In the standard INCL4 model, Pauli blocking of NN collisions is implemented on a statistical basis: phase space density around the final nucleon states is evaluated by counting nucleons in the neighbourhood of the representative points of the nucleons and the collision is accepted or avoided according to the probability given by the estimated blocking factors. This procedure allows to track the effects of the depletion of the Fermi sea as the collision process develops. However, since the initial Fermi sea in any particular event is represented by point particles taken at random, ``holes" may be present in the (phase space) Fermi sea. The importance of these holes diminishes with the evolution of the collision process, but they allow sometimes collisions that would be forbidden by a continuous uniform Fermi sea. It is shown in Ref. [7] that a good compromise, taking account of the depletion of the Fermi sea and reducing the effect of the holes, is obtained when a so-called strict Fermi blocking (i.e. accepting only collisions with final momenta above the Fermi momentum) is applied to the first collision.

As far as numerical codes are concerned, the standard INCL4 model is embodied in the INCL4.2 code and the improved version used in this work is sometimes referred as INCL4.4.3 in the specialized literature. In the following we will use the ABLA code as the evaporation code to be coupled to INCL4 (actually the so-called KHSv3p version, see Ref. [2] for detail).

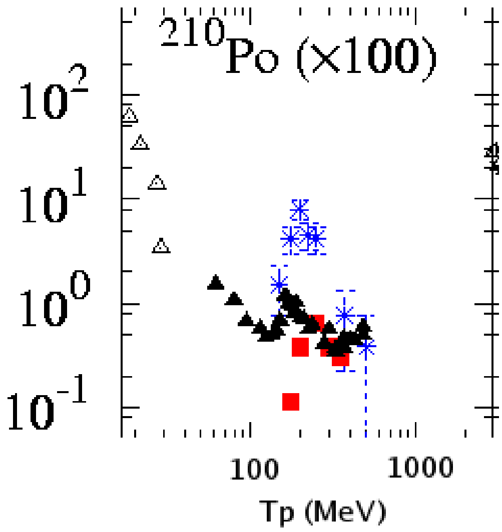

Fig. 1. Production cross section of ^{210}Po in p- ^{209}Bi reactions. Experimental data (triangles) are from Ref. [8]. The other symbols give the predictions of our standard (blue) and modified (red) versions of INCL4. All cross sections have been multiplied by 100 and are given in mb (or can be read directly from the vertical scale in fm ^{2}).

3. Residue production in p-^{209}Bi reactions

3.1.The A+1 case

The production of ^{210}Po has been measured in Ref. [8] for incident protons of energy between zero and ~400 MeV. The results are shown in Fig. 1. At low energy the reaction proceeds through the (p,γ) channel. This contribution is decreasing with energy, but the cross section is raising around 200 MeV, above which the reaction is largely due to the (p,π^0) channel. One can see that our modified model considerably improves the description of the data (the (p,γ) component is absent in our model). Of the various modifications that have been brought in our cascade model, the one which is largely responsible for the improvement of our predictions is the introduction of an energy-dependent mean field for the nucleons; the introduction of a potential well for the pion produces a lesser effect in the same direction. In Ref. [9], it is argued that the reactions proceeding through a single inelastic scattering are the most sensitive to the energy-dependence of the mean field. Indeed, what is conserved is the sum of kinetic and potential energy. When all the particles involved in a collision feel the same potential, the collision proceeds as in free space. This is no longer true when the potentials are energy-dependent. For realistic nuclear potentials, the energy dependence is roughly linear. In a elastic NN collision, the initial and final kinetic energies are roughly the same. This is true for potential energies and again, the situation as close to the one in free space. In an inelastic collisions, the initial and final kinetic energies may be very different. This will hold also for the potential energies. The difference will act as an effective Q-value, which will hinder pion-producing NN collisions. This effect will be manifest in events with a single inelastic collision. In most of the reactions, proceeding through several collisions, the effect of the energy-dependence is likely to be washed out.

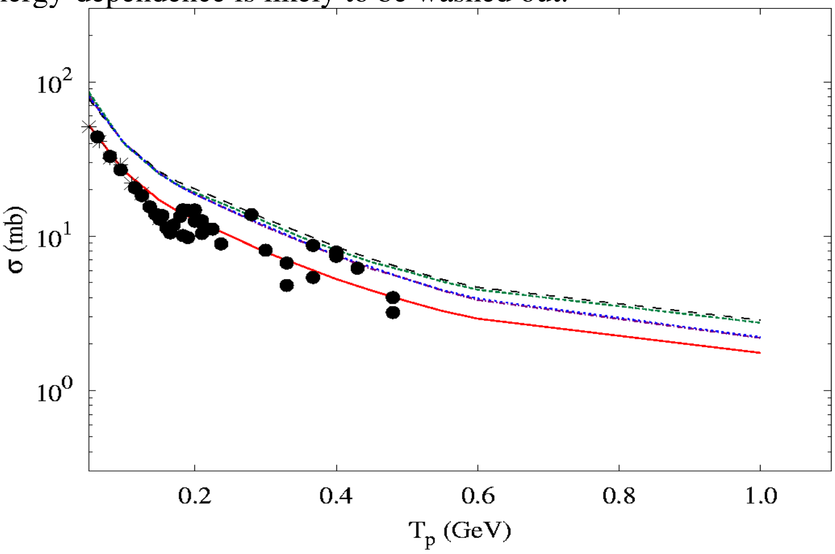

Fig.2. Production cross section of ^{208}Po in p-^{209}Bi reactions. Experimental data (dots) are from Ref. [10]. The curves give the predictions of our standard (black) and modified (red) versions of INCL4. See text for detail.

3.2.The Z+1 case

We will restrict here to the production of ^{208}Po, corresponding to the (p,2n) channel at the nucleon level and to (p,2nπ^0) and (p,pnπ^-) channels at the pion level. The comparison between our predictions and the data is given in Fig.2. Once again, the agreement is much better with the improved version. This time, the modification largely responsible for the improvement is the introduction of the strict Pauli blocking on the first collision. The energy-dependence of the mean field has practically no effect, the (p,2n) channel being mainly dominated by two elastic NN collisions. We verified that the contribution of the pion channels accounts for ~10% of the total cross section at 300 MeV incident energy, slightly above the effective threshold and for ~25% at 500 MeV.

4. Production of Bi isotopes in p-^{208}Pb reactions

Here we concentrate on the production of Z+1 isotopes (with A≤208). At the nucleon level, they correspond to the (p,xn) reactions, with x=1,2,etc. The data from Ref. [11] and our predictions are displayed in Fig.3. One can see that the agreement is quite improved with the modified version, especially for the heaviest isotopes. Let us consider the heaviest one, ^{208}Bi, which corresponds to the (p,n) channel. In this case, the improvement is due in quite similar proportions to three following three features: Pauli strict on the first collision, pion potential and energy-dependence of the nucleon men field. The first one is expected since ^{208}Bi can be produced in a single elastic scattering. The two others are important because the same isotope can be made by a single inelastic scattering and because the inelastic cross section is roughly equal to the elastic cross section at this energy. As the mass of the Bi isotopes diminishes, the number of collisions increases and the modifications brought by the three above-mentioned features progressively diminish.

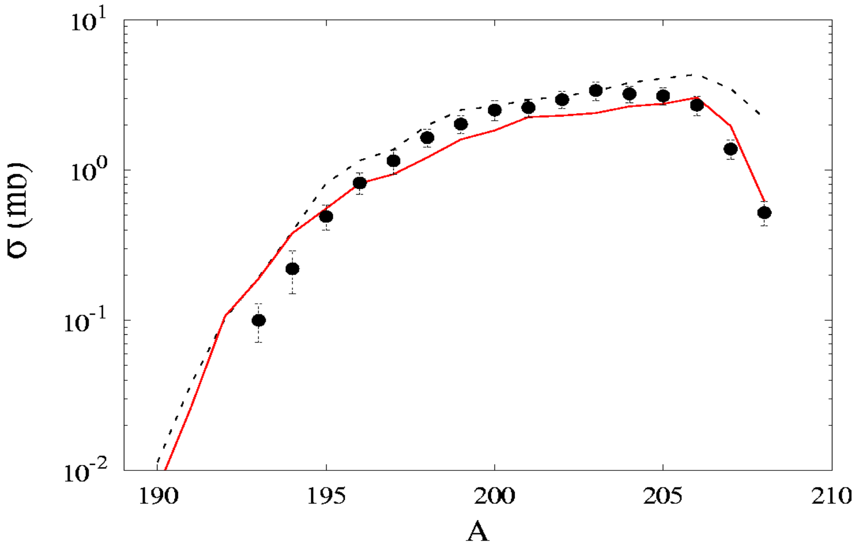

Fig.3. Production cross section of Bi isotopes of mass A in p- ^{208}Pb reactions. Experimental data (dots) are from Ref. [11]. The curves give the predictions of our standard (black) and modified (red) versions of INCL4.

5. Production of isotopes in a Pb-Bi thick target.

As we have indicated, the modifications brought in our INCL code are expected to yield important effects for the production of isotopes close the target, involving simple reaction mechanisms (in addition to the production of pions itself, which is extensively discussed in Refs. [1,7]. The effects of these modifications more or less vanish when the number of collisions increases. Nevertheless, we wanted to check whether these modifications can be of importance for a thick spallation target. For this, we performed a simulation of the chemical evolution of a thick target constituted of alternate disks of Bi and Pb, which was irradiated with a 590 MeV proton beam by the authors of Ref. [12]. The results of the isotopic analysis of the third disk, made of Bi in given in Fig. 4, with our predictions using MCNPX and our INCL4 model. First of all, as for the thin targets, our predictions for the two versions of INCL4 are very close except for special isotopes (such as ^{209}Po, where the difference reaches 70%). Globally, our predictions are rather close to the experimental data, except for the isomers. The discrepancy seems to arise from a wrong table of data in the version of MCNPX. Notice also that we give predictions for the Z+2 isotopes (Astatine).

6. Discussion and conclusion.

We have pointed out that the production of isotopes lying close to the target in the (N,Z) plane usually proceeds through one or few well identified channels and that reaction mechanisms can be assigned to one or few NN scatterings. For some of these isotopes, the dominant channel involve pion production: this is true for the isotopes at the boarder of the possibly created isotopes: A+1, Z+2, N+1. For the A+1 isotopes, the reaction mechanism corresponds to the pion fusion (p,π) process. When getting away from this boarder, the importance of pion-producing channels is progressively diminishing.

We have compared a few data concerning the production of these special isotopes with our improved version of the INCL4 model. The improvements bear on the treatment of the pion sector, with the introduction of a pion potential, on the improvement of the nucleon potential well (allowing energy-dependence) and on the treatment of the Pauli blocking (adopting a strict Pauli blocking on the first collision. In general we arrived at a better agreement than with with the standard version of our model. In addition, we showed that the pion fusion is dominated by an incoherent (collision) process and that the comparison point to a need of the energy-dependence of the mean field. Arguments indicating that the effect of the energy-dependence is washed out when the number of collisions increase have been given. Finally we have also performed with our new version a calculation of chemical modification in a thick target, indicating the relevance of our improved version for some radio-toxic isotopes.

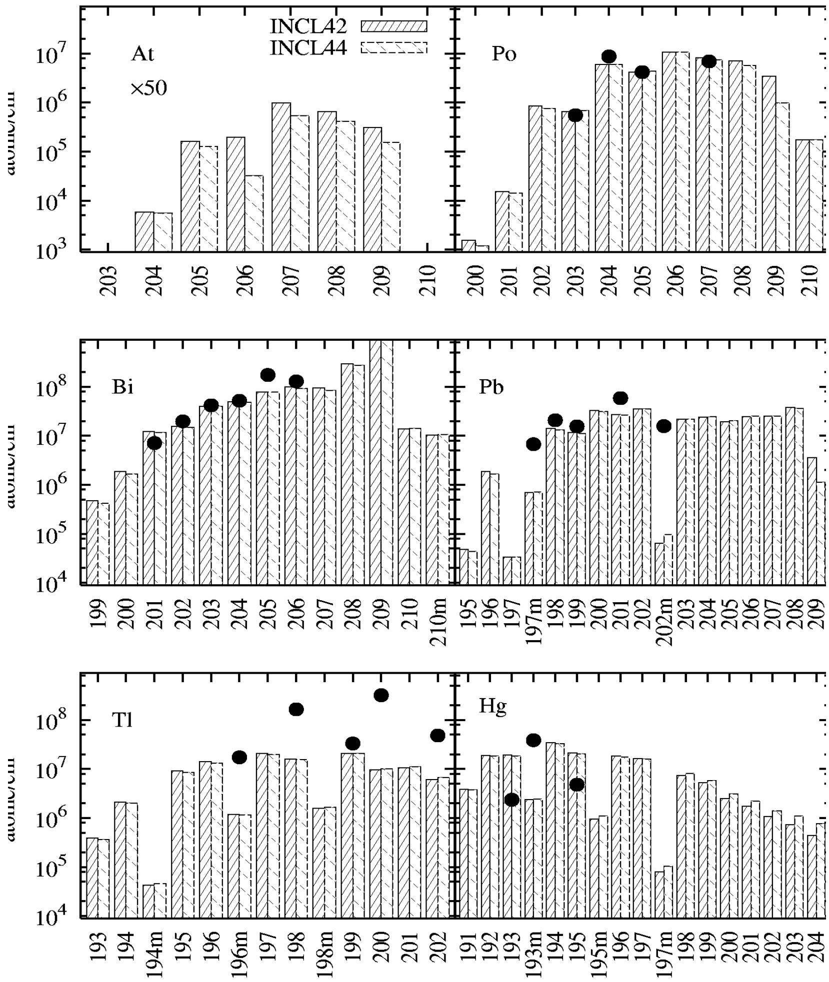

Fig.4 Isotopic distribution of the third disk in the thick Pb-Bi target used in Ref.[12] after irradiation. The ordinate given the isotopic concentration in numbers of atoms per cm3. The histograms give our predictions for the standard and modified versions of INCL4, according the indications mentioned at the top of the figure.

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