Evidence of Ni break-up from total production cross sections in p+Ni collisions

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The total production cross sections of light charged particles (LCPs), intermediate mass fragments (IMFs) and heavy reaction products of p+Ni collisions available in the literature have been compared with predictions of a two-step model in the proton beam energy range from reaction threshold up to ∼ 3 GeV. Model cross sections were calculated assuming, that the reaction proceeds via an intranuclear cascade of nucleon-nucleon collisions followed by evaporation of particles from an equilibrated, heavy target residuum. The shape of the excitation functions was well described by model calculations for all reaction products. The magnitude of the cross sections was reasonably well reproduced for heavy reaction products, i.e. for nuclei heavier than Al, but the cross sections for lighter products were underestimated. This fact was used as an argument in favor of a significant break-up contribution to the reaction mechanism. The present conclusions are supported by recently published results of investigations of differential cross sections in p+Ni collisions, which showed that hypothesis of the break-up of target nucleus is indispensable for a good reproduction of dσ/dE for LCPs and IMFs.

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I. INTRODUCTION

The aim of the present paper is to show the arguments, based on a systematic review of the energy dependence of total production cross sections in p+Ni system, that a break-up of the target nucleus is responsible for a large part of the total production cross sections of nuclides with the mass number smaller than A ∼ 30. It was shown in recent studies of p+Ni collisions at several energies [1, 2], that the break-up assumption leads to a very good description of energy and angular dependencies of dσ/dΩdE of light charged particles (LCPs), i.e., particles with Z≤2, and intermediate mass fragments (IMFs), i.e., particles with Z>2 but smaller than eventual fission fragments. The same effect has been previously observed for p+Au collisions [3, 4]. The p+Ni nuclear system has been chosen for the present analysis, because for this system the total production cross sections were measured in a broad range of ejectile masses [5, 6, 7, 8, 9, 10, 11] whereas the full squares are the result of the analysis of double differential cross sections integrated over angle and energy of ejectiles [1, 2]. The latter data agree perfectly with former ones for theses ejectiles where both methods were applied as, e.g., for 3,4He and 7,10Be. Thus, it can be conjectured, that they are equally trustworthy for other products. The advantage of the latter data is that they were measured for such LCPs and light IMFs, where other methods could not be applied. Due to this, a representative set of reac-

The present paper is organized as follows: Experimental data are presented in the next section where they are also compared with the theoretical cross sections evaluated in the frame of a traditional two-step model. The discussion of the results is presented also in this section whereas the summary with conclusions is given in the third section.

II. EXPERIMENTAL DATA AND THEIR DESCRIPTION BY A TWO-STEP MODEL

The total cross sections for products of p+Ni collisions at proton beam energies from the reaction thresholds up to ∼ 3 GeV available in the literature are presented on Figs. 1, 2, and 3 for LCPs and light IMFs, heavier IMFs, and target-like products, respectively. The data depicted by open triangles originate from experiments which measured total cross sections in a straightforward way [5, 6, 7, 8, 9, 10, 11] whereas the full squares are the result of the analysis of double differential cross sections integrated over angle and energy of ejectiles [1, 2]. The latter data agree perfectly with former ones for theses ejectiles where both methods were applied as, e.g., for 3,4He and 7,10Be. Thus, it can be conjectured, that they are equally trustworthy for other products. The advantage of the latter data is that they were measured for such LCPs and light IMFs, where other methods could not be applied. Due to this, a representative set of reac-
tion products, covering the full range of ejectile masses, was collected.

The experimental excitation curves for all products lighter than $^{44}$Sc increase in the studied energy range, indicating the beginning of a leveling of the cross sections at the highest energies (above $\sim 1 - 2$ GeV). For heavier products the rise of the cross section finishes at lower energies, the lower for the heavier product. The cross sections of these heavy products decrease monotonically after reaching a maximum and above 1 GeV a leveling of the excitation curves starts to appear.

The solid lines shown on the figures for a beam energy higher than 0.175 GeV represent calculations performed in the framework of the two-step model. The first step – the intranuclear cascade of nucleon-nucleon collisions with inclusion of possibility to emit complex LCPs due to coalescence of nucleons – was evaluated by means of the computer program INCL4.3 of Boudard et al. [12], and the second step – evaporation of particles from an equilibrated residuum of the cascade – by the GEM2 program of Furihata [13, 14]. The default parameter values, proposed by the authors of both programs, have been used, respectively. The lowest beam energy was chosen to be 0.175 GeV, because it is the energy at which double differential cross sections $d^2\sigma/d\Omega dE$ were measured and analyzed using these programs with success [1]. Still lower energies were not considered because it is improbable that intranuclear cascade can be applied at such low energies where the length of de Broglie wave starts to be too large for treating the nucleus as a set of individual nucleons - a prerequisite for the applicability of that model.

The comparison of theoretical lines with the experimental points leads to the following observations:

(i) The shape of all excitation curves is properly reproduced by the two-step model.

(ii) The magnitude of the cross sections is in average well reproduced for reaction products heavier than $A \sim 30$ (sometimes one observes even perfect reproduction like, e.g., for $^{36}$Cl, $^{36,38}$Ar or $^{44}$Sc).

(iii) Cross sections for all LCPs and IMFs lighter than $A \sim 30$ are systematically underestimated by the model.

The first two of the above observations suggest that the two-step model properly takes into account a dominating part of the reaction mechanism for heavy products. The third observation leads to the conclusion that for light products a different reaction mechanism plays the essential role.

It is reasonable to conjecture, that target-like nuclei are produced as remnants of the evaporation of light particles from an excited residuum of the intranuclear cascade. Such a typical spallation process should be well reproduced by the two-step model. However, the IMFs may be produced by various processes, i.e., they may be due to evaporation, may appear as heavy remnants of the evaporation or may occur from fragmentation of the target. The first two of these processes are taken into account in the two-step model but the third mechanism is not considered. Thus the fragmentation seems to be an obvious candidate for the process responsible for the observed inconsistency of the description of total production cross sections.

It was observed (cf., e.g., Ref. [15]), that for proton induced reactions at energies of the order of 10 GeV, a multifragmentation appears with a possible interpretation in terms of a nuclear liquid - gas phase transition. However, the enhanced – above the predictions of the two-step model – production of IMFs and LCPs is visible in Figs. 1 and 2 also at much lower energies. Moreover,
the multifragmentation mentioned above should proceed as the emission from a single source whereas it was shown in recent studies of p+Ni collisions \([1, 2]\) that at energies smaller or equal to 2.5 GeV two sources of IMFs are observed. These sources were interpreted as prefragments of the target appearing due to its break-up. Since a source can emit only particles with masses smaller than its own mass, the emission of particles from a single, target-like source contributes to the yield of all products whereas the emission from prefragments of the target is limited to products lighter than the heavier of both prefragments. Thus, only the break-up hypothesis is compatible with the fact, that a systematic enhancement of the experimental cross section above the predictions of two-step model appears for products with masses smaller than \(A < 2.5\) GeV.

To inspect more closely, for which products the break-up contribution is very significant, the differences of experimental production cross sections and those evaluated by the two-step model were for each product averaged over proton beam energies 1 – 3 GeV, and normalized to the energy averaged cross section of the two-step model. These relative differences are presented in Fig. 4 as a function of the product mass. It is clearly seen, that the relative differences are rather small and of a random character for products with mass larger than \(A \sim 30\) but not for heavier products.

FIG. 2: (Color online) The same as on Fig. 1 but for \(^{10,11}\)B, \(^{12}\)C, \(^{14}\)N, \(^{21,22}\)Ne, \(^{36}\)Ar, \(^{36}\)Cl, \(^{38}\)Ar, and \(^{44,45}\)Sc.

FIG. 3: (Color online) The same as on Fig. 1 but for \(^{46}\)Sc, \(^{44}\)Ti, \(^{48}\)V, \(^{52}\)Cr, \(^{54}\)Mn, \(^{55,56}\)Co, and \(^{56}\)Ni.
reaction products. In contrast, a different mass dependence of the relative difference is observed for products lighter than $A \sim 30$. In that mass region the experimental cross sections are larger than those calculated by two-step model for all products, giving room for the additional process. This indicates that for LCPs as well as for IMFs with a mass smaller than $A \sim 30$ the break-up contribution sets in. This contribution is dominating for IMFs because the relative difference is quite large for them; $\sim 4$ in the neighborhood of mass $A=10$ being about a factor two smaller for larger masses. For hydrogen and helium isotopes, the relative difference ($\sim 0.3$) is smaller than for IMFs, thus the relative break-up contribution is significant but not so large as for IMFs.

III. SUMMARY AND CONCLUSIONS

Due to the recent determination of total production cross sections $\sigma_{\text{exp}}$ and those from the two-step model $\sigma_{\text{TS}}$, averaged over beam energy of $1 - 3$ GeV as a function of product mass. The full squares show total cross sections for products lighter than $^{36}$Cl and the open squares correspond to heavier products. The horizontal solid line drawn for those latter products shows the average value of the relative difference of the cross sections, and the shadowed, horizontal bar presents the standard deviation of the relative difference.

The presently existing models of the reaction are not able to explain the observed effects, what was proved by extensive studies of the production cross sections performed recently for the $p^{56}$Fe nuclear system, very similar to the $p+Ni$ system studied in the present work, by two groups: [10] and [17]. In those papers the measured data have been compared with calculation results of 15 different codes for hadron-nucleus interactions: MCNPX (INCL, CEM2K, BERTINI, ISABEL), LAHET (BERTINI, ISABEL), CEM03 (.01, .G1, .S1), LAQGSM03 (.01, .G1, .S1), CASCADE-2004, LAHETO, and BRIEFF and still the agreement was not satisfactory. Moreover, the authors of Ref. [17] claimed, that "the most significant calculation-to-experiment differences are observed in the yields of the $A < 30$ light nuclei, indicating that further improvements in nuclear reaction models are needed".

The present hypothesis of the break-up of the target nucleus, which in a natural way explains the observed effects, offers an important hint in the development of microscopic transport codes, which up to now do not take such a process into account.

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