Neutron Production in Coincidence with Fragments from the $^{40}Ca + H$ Reactions at $E_{lab} = 357$ and $565\ AMeV$.

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Abstract

In the frame of the Transport Collaboration neutrons in coincidence with charged fragments produced in the $^{40}Ca + H$ reaction at $E_{lab} = 357$ and $565\ AMeV$ have been measured at the Heavy Ion Spectrometer System (HISS) facility of the Lawrence Berkeley National Laboratory, using the multifunctional neutron spectrometer MUFFINS. The detector covered a narrow angular range about the beam in the forward direction ($0^o - 3.2^o$). In this contribution we report absolute neutron production cross sections in coincidence with charged fragments ($10 \leq Z \leq 20$). The neutron multiplicities have been estimated from the comparison between the neutron cross sections, in coincidence with the fragments, and the elemental cross sections. We have found evidence for a pre-equilibrium emission of prompt neutrons in superposition to a 'slower' deexcitation of the equilibrated remnant by emission of nucleons and fragments, as already seen in the inclusive rapidity distributions.

1 Introduction:

We have studied the reaction $^{40}Ca + H$ at 357 and $565\ A\ MeV$. The experiment was performed at the Heavy Ion Spectrometer System (HISS) facility of Lawrence Berkeley National Laboratory. The complete experimental setup is described in detail in (Albergo et al., 1997). We used a liquid hydrogen target $0.254 \pm 0.004\ g/cm^2$ thick. The Neutron Spectrometer called MUFFINS was located on the incident beam line away from the charged particle detectors. MUFFINS is a modular detector made of several individual discs of NE102A plastic scintillator (Albergo et al., 1992; Albergo et al., 1995). We have measured the energy spectra, angular and rapidity distributions and total inclusive cross sections for neutrons emitted in these collisions, already presented at ICRC 1997. Some interesting insights on the reaction mechanism have been obtained by looking at the rapidity distributions (Tuvè et al.,1997).

In this paper we will present neutron production in coincidence with charged fragments. The neutrons were detected in coincidence with fragments of charge $Z \leq 20$ identified as the charge "islands" seen in the scatter plots of the raw analog-to-digital converter (ADC) response for the two charge measuring detectors located immediately after the target.

2 Results

The measured neutron cross sections (Tuvè et al.,1999), are reported in the Table. It is worthwhile to note that the cross section for $Z = 20$ is a measure of the neutron stripping cross section in the considered reaction. In our case the number reported below is the sum of the one- and two-neutron stripping contributions corresponding to the production of $A = 39$ and $A = 38$ fragments, respectively.

Z	$\sigma_{n,565\ A\ MeV}$ [mb]	$\delta\sigma$ [mb]	$\sigma_{n,357\ A\ MeV}$ [mb]	$\delta\sigma$ [mb]
20	20.	10.		
19	11.	7.		
18	28.	6.	13.	4.
17	18.	5.	8.	3.
16	35.	6.	12.	4.
15	20.	4.	17.	11.
14	30.	5.	15.	6.
13	18.	4.	6.	2.
12	21.	5.	6.	3.
11	8.	3.		
10	6.	3.		

At $565\ A\ MeV$ we have detected neutrons in coincidence with fragment charges in the range $20 \leq Z \leq 10$, while at $357\ A\ MeV$ the coincidence was taken with fragment charges in the range $18 \leq Z \leq 12$, due to lower statistics. For Z≤9 (at $565\ A\ MeV$) or Z≤11 (at $357\ A\ MeV$) it was impossible to identify the fragment charge and consequently the neutron cross section in coincidence with these fragments.

The neutron cross sections are reported in the upper panels of Fig. 1 as a function of Z for the two beam energies. In the lower panels of Fig. 1 we report the corresponding elemental production cross sections for the same reaction and energies (Knott et al., 1996; Chen et al., 1997). Also reported in each panel of Fig. 1 are the corresponding theoretical cross sections, calculated in the frame of the Boltzmann - Nordheim - Vlasov approach (BNV) (Bonasera et al., 1994).

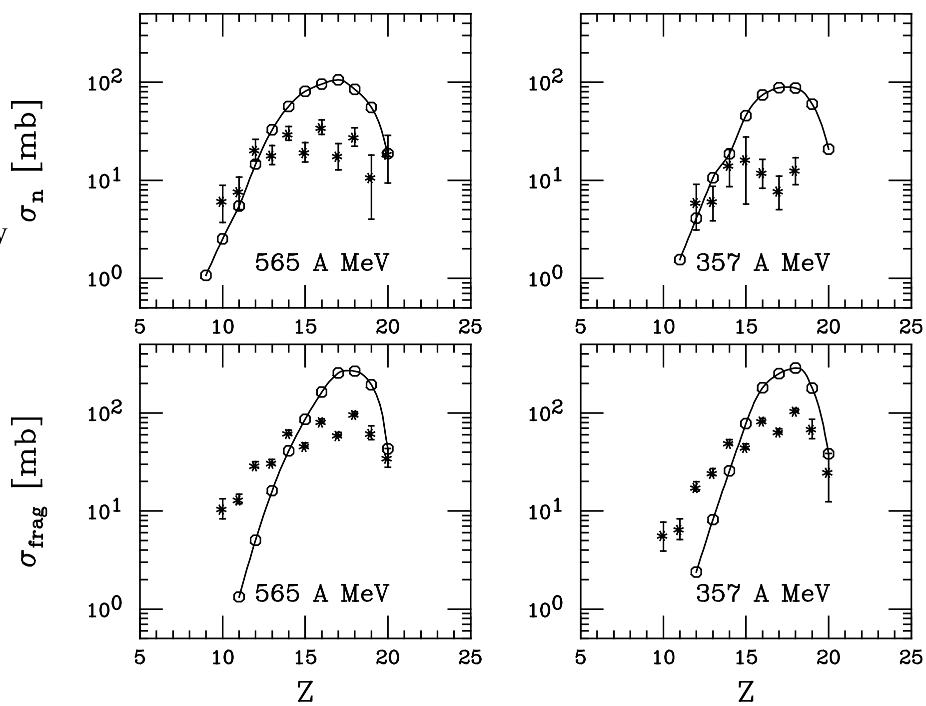

Figure 1: Upper left panel: Measured neutron cross sections σ_n (asterisks) for the $^{40}Ca + H$ reaction at $E_{lab} = 565\ A\ MeV$, in coincidence with charged fragments, compared with the BNV + phase space coalescence model (circles joined by a solid line). Upper right panel: same for $E_{lab} = 357\ A\ MeV$. Lower panels: Elemental production cross sections σ_{frag} (asterisks) for the same reaction and energies in comparison with calculations (circles joined by the solid line).

The experimental neutron production appears to be too small with respect to the number of free neutrons allowed by the size of the remnant fragment detected in coincidence. We have inferred the mean neutron multiplicity M_n vs. the remnant charge through the ratios between neutron and elemental cross sections $M_n = \sigma_n / \sigma_{frag}$, at the two beam energies. In Fig. 2 we report M_n vs Z_f. σ_{frag} has been obtained summing up all isotopic cross sections of Table I of ref. (Chen et al. 1997), but excluding, for Z=17, 18, and 19, the case in which a fragment with $N = 20$ has been produced.

The mean neutron multiplicity shows an increasing trend as Z decreases. Lower multiplicities are found at the lower energy. However, as it is possible to infere from the data plotted in Fig. 2, the neutron multiplicity is always much smaller than the "missing neutrons", defined as the number of neutrons necessary to form a ^{40}Ca from the remnant.

We cannot explain this observed "neutron defect" as due to clustering of neutrons in light fragments, particularly for the ones detected in coincidence with high-Z fragments, that correspond to peripheral collisions in which there are very few available nucleons, with unfavorable phase space conditions, to allow the necessary rate of light fragment emission. On the other hand, due to reverse kinematics, we expect most of the neutrons emitted by the remnant, which travels with a rapidity close to the beam rapidity, to enter the geometrical acceptance of MUFFINS.

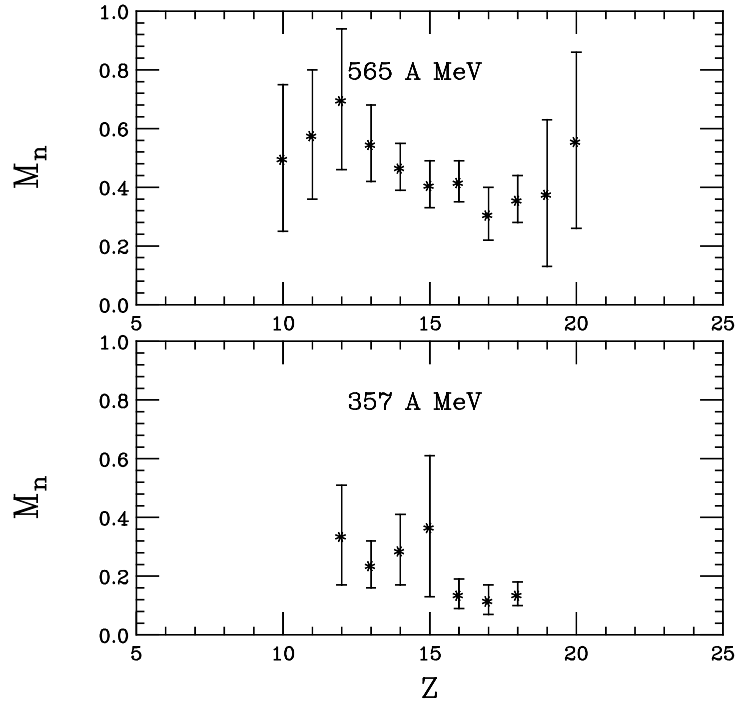

Figure 2: Mean neutron multiplicity versus Z for the $^{40}Ca + H$ reaction at $E_{lab} = 565\ A\ MeV$; (b): the same at $357\ A\ MeV$.

A reasonable way to explain the observed neutron defect seems to be the existence of a double reaction mechanism (Tuvè et al.,1999). So, as suggested also by other recent studies of reverse kinematics nuclear collisions (Hauger et al., 1998), we interpret our data as the result of a two-step reaction: the "neutron defect" is caused by those neutrons emitted in a pre-equilibrium stage. Since the system is not yet thermalized and so the energy is not shared between a large number of degrees of freedom they can take a larger fraction of the transverse momentum and escape out of the MUFFINS angular coverage, effectively reducing the neutron multiplicity. Around 0^o we detect on the contrary mainly neutrons emitted by the excited remnant, at low energy in the source frame, which show indeed the rapidly decreasing p_t distribution already discussed (Tuvè et al., 1997).

The energy dependence of the neutron production is better investigated looking at the ratios in Fig.3. In this figure we report the ratio $R_n = \sigma_n(E{=}565A\ MeV)/\sigma_n(E{=}357A\ MeV)$ in the upper panel and $R_{frag} = \sigma_{frag}(E = 565A\ MeV)/\sigma_{frag}(E = 357A\ MeV)$, for the fragments, in the lower panel. In the lower part of Fig. 3 the ratio R_{frag} shows that almost no energy dependence is observed in the elemental cross sections for fragment charge from the beam charge down to $Z \simeq 15$.

This is in quite good agreement with BNV calculations, which reproduce relative cross sections better than absolute ones (Tuvè et al.,1999). The situation is less clear for the neutron data due to larger error bars. Anyhow, the general trend observed in the data, upper part of Fig. 3, seems to be consistent with the theoretical predictions and with the fragment production data if one considers that at the lower incident energy due the weaker focussing in the forward direction more neutrons are lost outside the angular range covered by MUFFINS (0^o – 3.2^o). This is suggested, on the other hand, by the lower values of multiplicity at E=357 A MeV. In addition, the trend observed for both ratios of Fig. 3 could be traced back to the centrality of the collisions: smaller fragments are produced in central collisions while peripheral collisions are responsible for the production of fragments with $Z \geq 15$. The more destructive central collisions bring in a larger energy dependence.

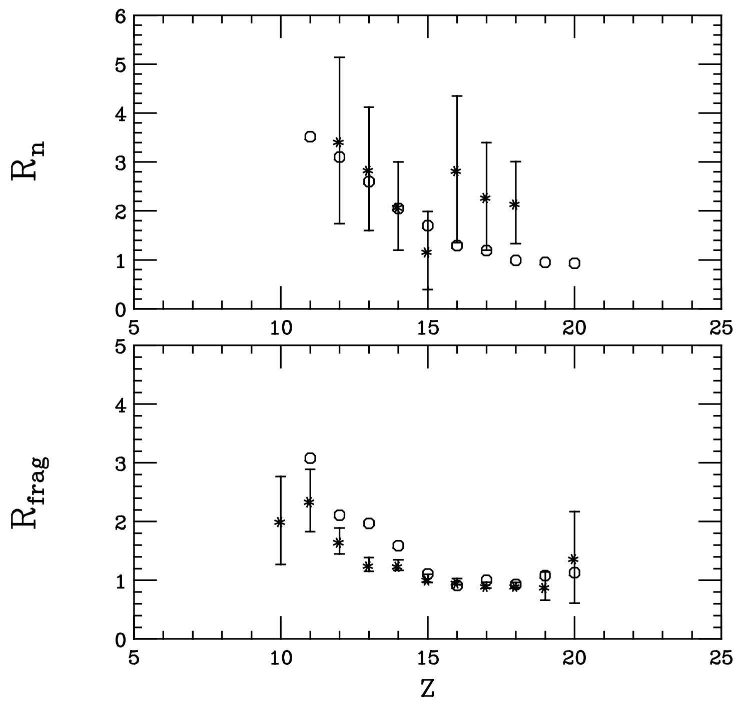

Figure 3: Upper panel: R_n, see text, (asterisks) versus Z; Lower panel: R_{frag}, see text, (asterisks) versus Z in comparison with calculations (circles).

In conclusion, we have presented new neutron production data in coincidence with fragments emitted in the reaction $^{40}Ca+H$ and suggested an interpretation for the inferred mean multiplicity and energy dependence of the neutron cross sections.

Our data show evidence of a two-step reaction mechanism already discussed in connection with very asymmetric nuclear collisions (Mahi et al., 1988; Hauger et al., 1998). We interpret the observed neutron defect as due to a pre-equilibrium emission of energetic neutrons that escape from the angular coverage of our detector. The neutrons detected around 0^o are, therefore, mainly emitted by the remnant in the second step of the reaction.

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