PARAMETERS OF EMITTING SOURCES IN Ar–Ni REACTION AT 77 MeV/u*

K. Wosińska[a], J. Pluta[a], F. Hanappe[c], L. Stuttge[d], J.C. Angelique[e]
Z. Basrak[i], B. Benoit[c], E. de Goes Brennand[c], G. Bizard[e], J. Colin[e]
G. Costa[d], P. Desesquelles[f], O. Dorvaux[d], D. Durand[e], B. Erazmus[b]
A. Kieliszek[a], S. Kuleshov[h], R. Lednicky[g], P. Leszczyński[a]
M. Marques[e], Th. Materna[c], K. Mikhailov[h], K. Miller[a]
G. Papatheofanous[c], T. Pawlak[a], M. Przewłocki[a], A. Staranowicz[a]
A. Stavinsky[h], B. Tamain[e], and A. Vlasov[h]

[a] Faculty of Physics, Warsaw University of Technology
Koszykowa 75, 00-662 Warsaw, Poland
[b] SUBATECH, UMR Univ., EMN, IN2P3/CNRS
4 rue A. Kastler, 44307 Nantes, France
[c] Universite Libre de Bruxelles, CP229
Av. F. D. Roosevelt, 50, B1050, Bruxelles, Belgium
[d] IRES, IN2P3-CNRS / Universite Louis Pasteur
BP28, F67037 Strasbourg Cedex 2, France
[e] Laboratoire de Physique Corpusculaire, IN2P3, CNRS/ISMRA
14050 Caen Cedex, France
[f] ISN, IN2P3/CNRS, et Universite J. Fourier
53 Av. des Martyrs, 38026 Grenoble Cedex, France
[g] Institute of Physics, Czech Academy of Sciences
Na Slovance 2, 18221 Prague 8, Czech Republic
[h] Instute of Theoretical and Experimental Physics
B. Cheremushinskaya 25, 117259, Moscow, Russia
[i] Ruder Bošković Institute, P.O. Box 180, HR-10 002 Zagreb, Croatia

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Two-neutron correlation functions as well as single neutron energy spectra were used to determine the parameters of the emitting sources in Ar–Ni reaction at 77 MeV/u. The neutrons were registered in angular ranges 4°–22° and 55°–66°. By a choice of the neutron energy range and measurement angles we are able to determine the space-time parameters of the preequilibrium and the quasi-projectile separately. The source velocities and temperatures were determined by fitting the multisource model parameters to the single-neutron inclusive energy spectra. The space-time parameters were extracted from the fit of correlation functions with a Gaussian (space) and exponential (time) distributions.

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1. Introduction

Analysis of two-particle correlation function is a powerful method of determining the lifetime and radius of a particle emitting source. In this paper two-neutron correlation function, free of Coulomb effects, was analysed.

The experimental data were obtained in E286 experiment performed at GANIL [1]. The neutrons were detected in a block of 45 detectors installed in the forward direction (4°–22°). Another block of 15 detectors was placed at angles (55°–66°). These modules were placed at different distances from the target in order to eliminate the parasite effects following the method of Ref. [2].

2. Equilibrated multisource model

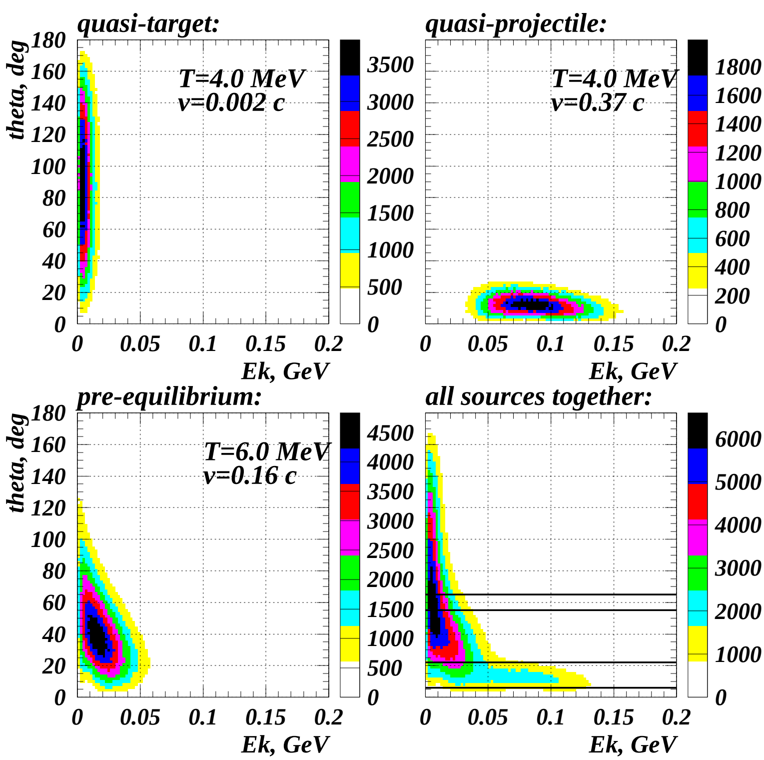

Fig. 1. Kinetic energy *vs* emission angle of neutrons in the frame of equilibrated multisource model. The lines in the lower right part indicate the experiment acceptance region.

The data were compared with the equilibrated multisource model described in [3]. The model assumes that particles are emitted from three sources related to two stages of the reaction.

The first one — relatively fast — gives contribution to the particles emitted at mid-rapidity (the preequilibrium source). In the second stage particles are emitted from two low-temperature sources with long lifetimes (the quasi-target and the quasi-projectile). Fig. 1 shows kinetic energy *versus* angle distributions of neutrons coming from different sources in the frame of the equilibrated multisource model for the parameters indicated in the figure.

The source parameters: temperature T and velocity v were determined using single-particle inclusive energy spectra (Sect. 3). The space coordinates of the emission point (x, y, z) were taken from a spherical Gaussian probability distribution with a dispersion r_0^2. The emission time (t) was sampled from an exponential probability distribution $P(t) \sim \mathrm{e}^{-t/\tau}$. The values r_0 and τ characterize the space-time dimension of each source. The root mean square radius of the source is $\sqrt{3}$ times larger than r_0.

Right lower part of Fig. 1 relates to the neutrons from all sources together. The lines indicate the experimental acceptance of angular region. The neutrons with kinetic energy larger than 40 MeV detected at the forward detectors come mainly from the quasi-projectile. On the other hand the neutrons with kinetic energy larger than 10 MeV detected at the side detectors are emitted predominately from the stage of preequilibrium.

3. Single-neutron inclusive energy spectra

Fig. 2 presents the single-neutron inclusive energy spectra measured at different emission angles.

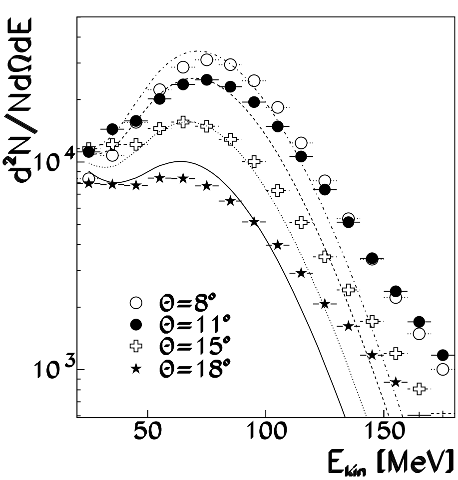

Fig. 2. Neutron energy spectra measured for the emission angles from $\theta = 8°$ to $\theta = 18°$. The curves correspond to the fits with the two-equilibrated-source model.

The curves correspond to the fit with the two-equilibrated source model described by formula (1). We assume that the contribution from the quasi-target in our acceptance region is negligible (see Fig. 1).

$$\frac{d^2\sigma}{dEd\Omega} = N_1\sqrt{E}\exp\left(-\frac{E+E_1-2\sqrt{E_1E}\cos\Theta}{T_1}\right) + N_2E\exp\left(-\frac{E+E_2-2\sqrt{E_2E}\cos\Theta}{T_2}\right), \qquad (1)$$

where the first component corresponds to the preequilibrium (volume evaporation) and the second one — to the quasi-projectile (surface evaporation) [4]. E and Θ are, respectively, the kinetic energy and the angle of emission of the neutrons in the laboratory rest frame, N_1 and N_2 are the normalization constants, T_1 and T_2 — the preequilibrium and the quasi-projectile "temperature" parameter, $E_i = m/\sqrt{1-{v_i}^2} - m$ $(i = 1, 2)$, where m is the neutron mass and v_i is the source velocity in the laboratory system. All fitting parameters were free. The best values of "temperature" parameters and the velocity are listed in Table I.

TABLE I

Parameters of the two equilibrated sources fitted to the inclusive neutron spectra (Fig. 2). v_i and T_i are velocity (in c units) and temperature (in MeV) of the i-th source, respectively.

preequilibrium		quasi-projectile	
v_1	0.16	v_2	0.37
T_1	6	T_2	4

The curves in Fig. 2 reflect the general tendency resulting from two source assumption. The values of found velocities correspond to the expected values: the cms velocity for the preequilibrium and the projectile velocity for the quasi-projectile. The deviations at highest energies and large angle (18°) can be attributed to the dynamical effects in the fast stage of the reaction (nonthermalised component of the preequilibrium stage at highest energies and large detected angle where the mixture of two components is the highest).

4. Two-neutron correlation function

The experimental correlation functions are presented in Fig. 3.

Fig. 3(a) relates to neutrons coming mainly from the quasi-projectile ($E_{\text{kin}} > 40$ MeV, $\Theta < 22°$). The experimental correlation function is compared with the theoretical one. The calculations were performed using the code based on the Ref. [5]. Neutrons were generated from a single Maxwellian source with a temperature of 4 MeV, velocity 0.37, radius 1.2 fm and lifetime 1500 fm/c. Fig. 3(b) relates to neutrons coming mainly from the preequilibrium (E_{kin} >10 MeV, $55° < \Theta < 66°$). The corresponding theoretical correlation functions has been obtained for the single source with temperature of 6 MeV, velocity 0.16, radius 3.6 fm and lifetime 30 fm/c.

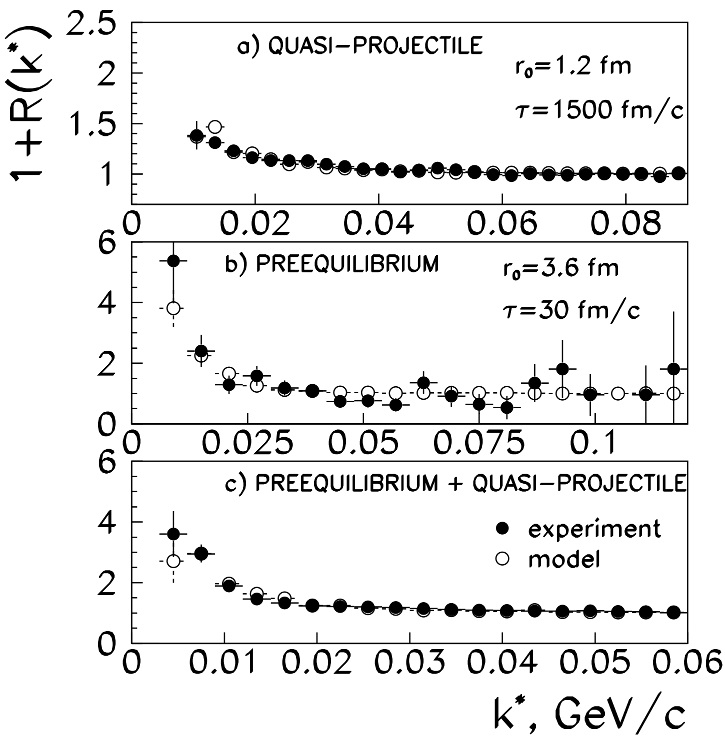

Fig. 3. The experimental correlation functions: (a) for neutrons emitted forward ($\Theta < 22°$) at energies $E_{\text{kin}} > 40$ MeV, (b) for neutrons emitted at directions $55° < \Theta < 66°$ at energies $E_{\text{kin}} > 10$ MeV, (c) for neutrons emitted forward at energies $E_{\text{kin}} > 10$ MeV. Theoretical correlation functions are described in the text.

Accuracy of the determination of the space-time parameters is shown in Fig. 4(a) and (b), which presents the values of χ^2 per degree of freedom for different combinations of r_0 and τ. Note that the χ^2 "valley" is strongly asymmetric in the case of r_0 dependence for quasi-projectile. The obtained value 1.2 fm corresponds to the situation of long duration particle emission from rather a compact source with the size approximately equal to the half of the projectile. The value 1.2 fm is close to the minimal radius value ($r_0 >$

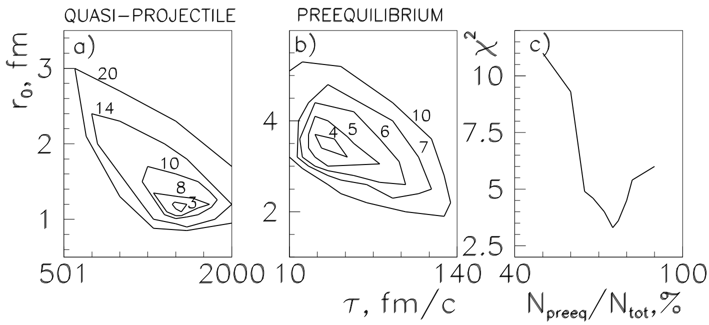

Fig. 4. (a) and (b): Contour diagram of χ^2 value per degree of freedom determined by comparing the theoretical functions to the data shown in Fig. 3(a) and 3(b) as a function of the quasi-projectile and the preequilibrium space-time parameters. (c): χ^2 value per degree of freedom for different probability of neutrons emission from the preequilibrium: $N_{\rm preeq}/N_{\rm tot}$, where $N_{\rm preeq}$ — number of neutrons emitted from the preequilibrium, $N_{\rm tot}$ — number of all neutrons.

1 fm) for which the square-well approximation is reasonably accurate [5]. The model correlation function is in good agreement with the experimental one for source radius in the range 1.2–1.6 fm and lifetime 1200–1800 fm/c. It should be noticed that the number of neutrons registered in the side detectors was rather small and the related correlation functions (Fig. 3(b)) have been calculated with large errors. For that reason the parameters of the preequilibrium have been determined rather crudely (source radius in the range 3.0–4.0 fm, lifetime 20–90 fm/c). Fig. 3(c) shows the experimental correlation function for neutrons emitted forward ($\Theta < 22°$) at energies $E_{\rm kin} > 10$ MeV, coming both from the quasi-projectile and the preequilibrium. In this case the neutrons have been generated from two-source model: the preequilibrium and the quasi-projectile by employing parameters determined previously in the frame of single-source model (Fig. 3(a) and (b)). According to Fig. 4(c) probability of the emission from the preequilibrium at the solid angle of 4π is taken as 75 % (minimum of χ^2 value). Other models applied to the same experiment give the similar value: in the Simon model [6] about 70 % of neutrons come from the preequilibrium, in the Landau–Vlasov model [7, 8] — about 60%.

5. Conclusions

The equilibrated source model is useful for the description of particle emission, especially for sources with long lifetimes. In the frame of this model the space-time parameters of the emitting sources have been determined. However, dynamical models, like QMD or the semiclassical Landau–Vlasov model, seem to be more appropriate for the description of the first fast stage of the reaction.

REFERENCES

[1] M. Przewłocki *et al.*, *Acta Phys. Pol.* **B411**, 379 (2000).

[2] J. Pluta *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A411**, 417 (1998).

[3] J. Pluta *et al.*, *Eur. Phys. J.* **A9**, 63 (2000).

[4] A.S. Goldhaber, *Phys. Rev.* **C17**, 2243 (1978).

[5] R. Lednicky, V.L. Lyuboshitz, *Sov. J. Nucl. Phys.* **35**, 770 (1982); *Proc. Int. Workshop on Particle Correlations and Interferometry in Nuclear Collisions, CORINNE 90, Nantes, France, 1990*, ed. by D. Ardouin, World Scientific 1990, p. 42.

[6] D. Durand, *Nucl. Phys.* **A541**, 266 (1992).

[7] Z. Basrak, Ph. Eudes, P. Abgrall, F. Haddad, F. Sébille, *Nucl. Phys.* **A624**, 472 (1997).

[8] Z. Basrak, *Nukleonika* **43**, 337 (1998).