LIGHT PARTICLE SPECTRA: ENERGY DISSIPATION IN ANTIPROTON–NUCLEUS INTERACTIONS*

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The process of energy dissipation in antiproton-nucleus interactions is studied by multiplicities and energy spectra of $n, p, d, t, \pi^{\pm}$ and $K^{\pm}$ for thirteen targets from carbon to uranium. By these observables the energy transfer to the nucleus and the excitation energy of the equilibrated system was determined by two methods. The results are compared with intranuclear cascade predictions.

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Antiproton ($\bar{p}$) annihilation at rest in nuclei presents a very interesting tool for studying hot nuclear matter by the fact that $\bar{p}$ heats up the nucleus without transferring large linear and angular momentum. The process of energy dissipation from the pionic system (formed by annihilation) to the nucleus and the result of this process, the excitation energy of the equilibrated compound nucleus, is important for the investigation of such excited nuclei.

The first stage of the energy transfer can be investigated by measurement of pion spectra after annihilation [1, 2]. For the determination of the thermal excitation after the fast intranuclear cascade this method lacks the (important) information of the energy carried off by fast particles before

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thermal equilibrium is achieved. A measure for the excitation energy E* is the total mass loss determined from the distribution of residual nuclei by measuring the gamma spectra of the irradiated targets [3]. A distribution of the mass loss can be interpreted as an E* distribution but a quantitative analysis requires an approach for the mean energy escaping per nucleon.

A more direct way is the experimental measurement of all emitted particles in one experiment. An approach to this ideal (because of the required complete energy spectra and particle yields) measurement was an experiment with stopped antiprotons, where the inclusive energy spectra of $n, p, d, t, \pi^{\pm}$ and $K^{\pm}$ have been measured for 13 targets in a recent experiment. A beam of 2 to $5 \cdot 10^4$ $\bar{p}/s$ with momentum of 200 MeV/c (about 21 MeV) from the LEAR at CERN was degraded in mylar and kapton foils and in a plastic scintillator in front of the target. The thickness of the absorbers was adjusted for stopping the antiprotons in the center of the thick targets (^{12}C, ^{27}Al, ^{28}Si, ^{40}Ca, ^{64}Cu, ^{92}Mo, ^{100}Mo, ^{nat}Ag, ^{165}Ho, ^{181}Ta, ^{197}Au, ^{209}Bi, ^{238}U). Five liquid scintillator detectors were used in combination with different plastic scintillators in front of each detector. The correlation between time-of-flight and light output of both scintillators, as well as the pulse shape (sensitive to ionisation density) of the liquid scintillator NE213 were exploited to identify the different particles [4]. The inclusive energy spectra of the detected particles for one target (uranium) are shown in Fig. 1.

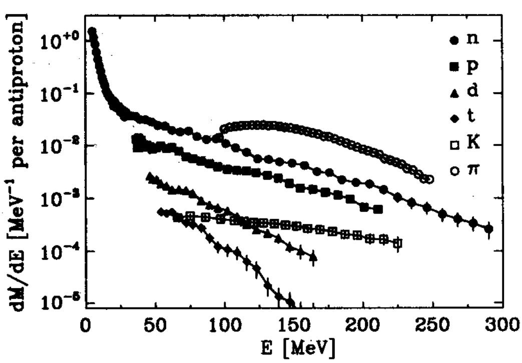

Fig. 1. Energy spectra of all identified particles from $\bar{p}$-capture in uranium. The data points are connected by lines.

The spectral shape is assumed to be given by maxwellian-like distributions for isotropic emission of neutrons

$$\frac{dM}{dE} = \sum_{i=1}^{k} \frac{2M_i}{\pi^{1/2}T_i^{3/2}} \sqrt{E} \exp\left(-\frac{E}{T_i}\right) , \tag{1}$$

where k is the number of sources (one thermal and one or two preequilibrium) which are assumed to be at rest in the laboratory system. The spectra for protons, deuterons and tritons were fitted by a single component

$$\frac{dM}{dE} = \frac{M}{T^2}(E - V_c)\exp\left(-\frac{E - V_c}{T}\right) \tag{2}$$

because only the highly energetic component could be measured in the experiment (see Fig. 1). V_c is the Coulomb barrier of the charged particle in each target.

The experimental yields of charged pions and kaons (extrapolated to neutral mesons), assuming a mean kinetic energy of 210 MeV per pion [5], allow the determination of the mean fraction $E_{\rm trans}$ transferred from the multi-pion system to the baryonic system of A nucleons *via* scattering and absorption of mainly pions. The first stage of the intranuclear cascade (INC) is dominated by sequential two-body collisions of the annihilation pions with nucleons within the nucleus. In this early stage, highly energetic nucleons escape directly leading to a large slope parameter which reflects the momentum distribution of the primordial pions. After this direct cascade a highly excited but not fully equilibrated nucleus is formed. On the way to the attainment of thermal equilibrium the excited system may also emit particles originating from nucleon-nucleon interactions (second source in (1)). From the fitted observables the mean kinetic energy can be detemined for neutrons by

$$\langle E_{n,i}^{\rm kin}\rangle = \tfrac{3}{2}T_i\,, \tag{3}$$

and for light charged particles by

$$\langle E_{\rm lcp}^{\rm kin}\rangle = V_c + 2T\,. \tag{4}$$

The nearly complete description of the cascade and preequilibrium stages by the measured observables yields the part of energy $E_{\rm PE}$ emitted prior the thermal equilibrium

$$E_{\rm PE} = \sum_m \langle M_m\rangle\left[\langle E_m^{\rm kin}\rangle + \langle B_m\rangle\right], \tag{5}$$

where $\langle B_m\rangle$ is the mean binding energy of particle m [6], and $m = \{n, p, d, t\}$[1]. The excitation energy E^* retained by the nucleus following the fast processes ($\tau \le 10^{-22}s$) can be obtained as the difference of the transferred

[1] The inclusion of ^{3}He and α emission, measured in [7], in the energy balance increases $E_{\rm PE}$ only by about 0.6%, much less than the statistical error.

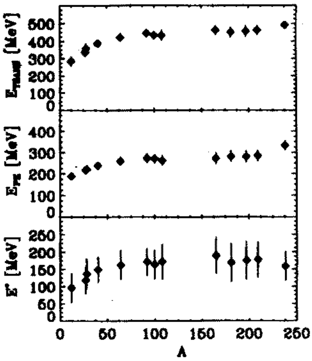

Fig. 2. Mass dependence of the mean energy transferred from the pion system to the nucleon system E_{trans}, of the energy emitted prior to thermal equilibrium E_{PE}, and of the average excitation energy gained by the compound nucleus E^*, respectively.

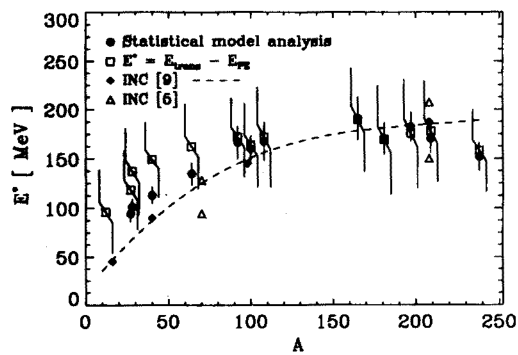

Fig. 3. Mass dependence of the experimentally determined excitation energy deposited in the decaying nucleus E^* by two methods (see text) compared with INC calculations [5, 9]. Dashed line is drawn through the calculated INC values.

energy E_{trans} and the energy E_{PE}. The dependence of these energies on the target mass is shown in Fig. 2.

A second, independent method to deduce the thermal energy of the excited nucleus is the comparison of the yield and the shape of spectra of evaporated neutrons in the experiment with calculations which we performed within a statistical model [8].

The excitation energies deduced by these different methods are compared to INC predictions by Cugnon *et al.* [9] and Iljinov *et al.* [5] in Fig. 3. Both methods agree well, especially for medium and heavy targets. The nuclear excitation by means of $\bar{p}$-annihilation at rest seems to saturate with increasing target mass at mean values between 150 and 200 MeV. The discrepancy for the lightest nuclei may result from the used uniform parameter set for level densities in the model calculations over the whole mass range, which might not be adequate for light nuclear systems. The INC calculations show the same saturation of the mean excitation energy with increasing target mass [9].

Our systematic experimental results for excitation energies of the equilibrated nuclei following $\bar{p}$-annihilation at rest lead to the conclusion that, on the average, only about 10% of the annihilation energy (1.88 GeV) can be converted to thermal excitation of nuclear matter. In particular, the excitation energy per nucleon becomes less than 2 MeV/A (except the lightest nuclei). This value indicates that only a small amount of events will gain enough energy (larger than 3 MeV/A [10]) needed for the onset of multifragmentation. The use of high-momentum antiprotons seems more promising for inducing multifragmentation because the annihilation pions will be focussed more into the nucleus and therefore more energy may be deposited in the nucleus, as shown by an INC calculation for a Mo nucleus [11].

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