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MONITORING SYSTEM FOR RELATIVISTIC PARTICLES AND NUCLEI

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1. INTRODUCTION

Precise measurements of a beam flux of relativistic particles and nuclei over a wide range of energies and intensities is a complex experimental problem. Monitoring systems use various types of detectors such as scintillators [1], ionization chambers [2] as well as their combinations. The foil activation technique [3] is also applied succesfully. However, this technique requires a knowledge of the cross sections of monitoring reactions in a wide interval of energies with a good accuracy.

In the present paper a new technique and results of its application for the measurement of a beam flux of protons, deuterons, ^{4}He- and ^{12}C-ions accelerated at the Dubna synchrophasotron are described. The proposed experimental technique allows one to measure the extracted currents of charged particles up to the maximum limit and to calibrate the systems used for measuring the absolute intensity. Using this monitoring system, we have measured the total cross sections of monitoring reactions $^{27}Al(p,X)^{24}Na$ and $^{27}Al(^{12}C,X)^{24}Na$ at 3.65 AGeV.

2. MONITORING SYSTEM

The flux measurement technique is based on the registration of charged particles by means of a narrow nuclear emulsion layer rotating in a beam as well as on a parallel counting of neutrons produced by a primary beam and secondary particle interactions in a block of the Pb-converter placed after the experimental apparatus. It should be noted that the dimensions of the converter are larger than the beam diameter. The total number of particles registered by the nuclear emulsion corresponds to the sum of neutron counts in a given converter. In our experiments we have used the Pb-converter in which neutrons are detected by means of the standard fission chambers KNT-8 [4].

It is well-known that beams of particles have a complex profile, and also their intensities vary with radius and azimuthal angle. In order to eliminate the difficulties and necessary corrections caused by these facts, we have used the counts of events recorded by the nuclear emulsion rotating in a beam. A layer of the emulsion 20 cm long and from 3 to 5 cm wide was vertically mounted on the axis of an engine which rotates with a frequency of 10 Hz. The vertical intersection of the rotating emulsion layer with the beam (see fig.1) enables only the particles to be recorded by the part of the layer area at distance R

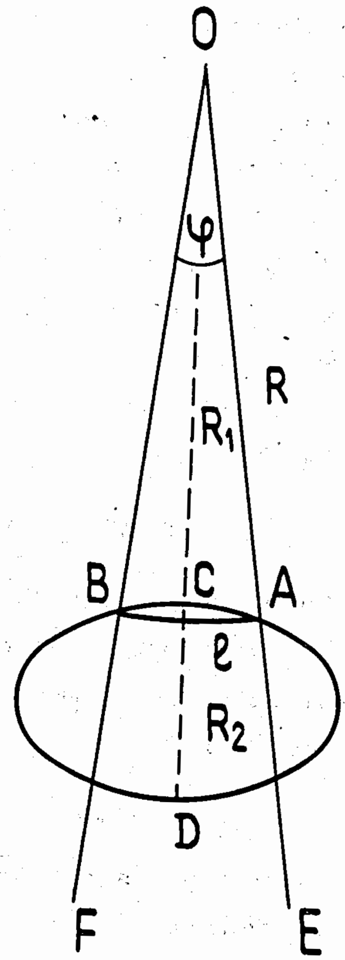

Fig.1. Schematic drawing of the experimental arrangement of rotating nuclear emulsion in a particle beam: O - engine axis according to the beam direction perpendicular to the figure plane: $OC=R_1$ - minimum radius; $OD=R_2$ - maximum radius; ϕ - angular interval of beam intersection at radius R=OA; ℓ - length of the part of the area ΔS at a given R; OE=OF -layer of the emulsion.

from the axis of motion. The intersection of the layer surface from minimum, R_1, to maximum, R_2, distances overlapped the whole beam. The appropriate summing of particles recorded over a narrow area of the emulsion layer from R_1 to R_2 eliminates the influence of some instability as well as the profile of a given beam. As can be seen from fig.1, the part of the area ΔS intersects the beam at distance ℓ between points A and B. It is evident that multiple intersections of the layer with a beam per cycle as well as an appropriate recording of particles over the area ΔS can be averaged over the length ℓ. Denoting the number of registered particles over ΔS as $i(R,\Delta S)$, the total intensity can be expressed as

$$J_1\,(R,\Delta S) = i(R,\Delta S)\ell = i(R,\Delta S)\,R\phi . \qquad (1)$$

Taking into account that the part of the area ΔS has been irradiated only for the time proportional to $\phi/2\pi$, the total intensity must be multiplied by the inverse factor, i.e.

$$J\,(R,\Delta S) = 2\pi R\, i\,(R,\Delta S) . \qquad (2)$$

The appropriate summation of ΔS from R_1 to R_2 yields the total beam flux

$$J_o = \sum_{R_2}^{R_1} 2\pi R\, i(R)\frac{1}{\Delta S} . \qquad (3)$$

Each element of this sum gives the intensity distribution for a given R.

Figure 2 documents a microphotography of the tracks of registered ^{12}C nuclei which differ reliably from background ones having the same vertical directions and

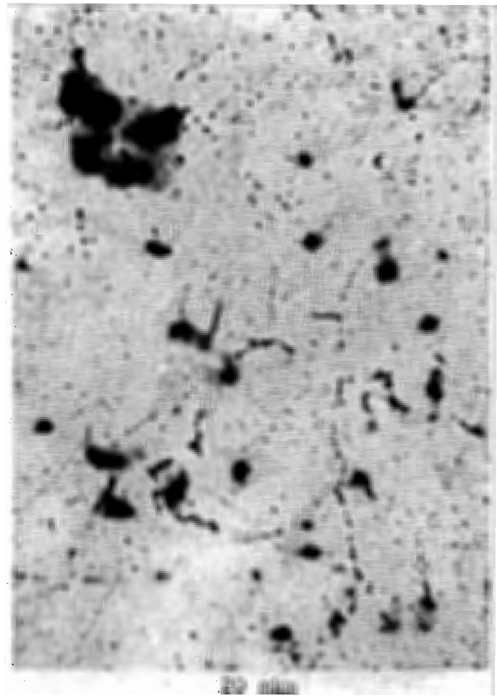

Fig.2. Microphotography of the tracks registered by nuclear emulsion for ^{12}C-ion irradiation.

ionization characteristics. The intensity distributions for proton and ^{12}C-ion irradiations are shown in fig.3. As can be seen from this figure, the instability of the beam of ^{12}C-ions is apparent. The total flux of protons, recorded by two independent observers, is 6.65×10^8 and 6.67×10^8, respectively, which corresponds to a statistical uncertainty of about 1%.

The average value of J = $(6.66\pm0.13)\times10^8$ also includes the uncertainty corresponding to the error in the R determination. The intensity distributions for two independent measurements in the beam of relativistic deuterons are presented in fig.4. The ratio of the total intensities in these measurements has reached 1.76±0.05. Parallel measurements with the use of the registration of neutrons with 21 fission chambers KNT-8 placed at different points of the Pb-converter have yielded a

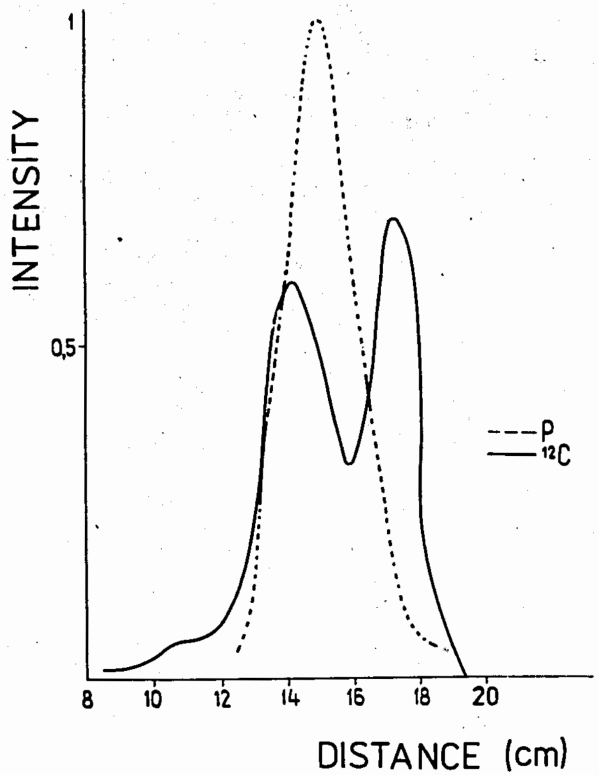

Fig.3. Intensity distributions of protons and ^{12}C-ions normalized to the appropriate area.

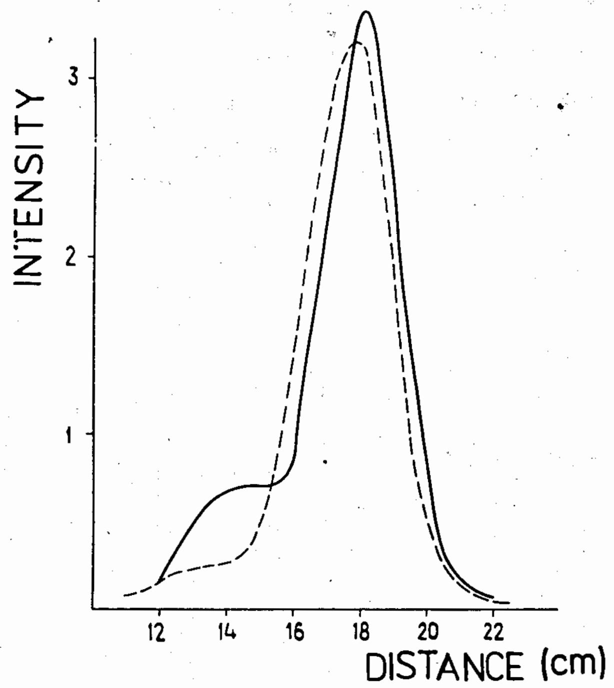

Fig.4. Intensity distributions of deuterons for two independent measurements.

ratio of 1.65±0.04 . There is an agreement between both independent monitors from an average value of 1.70±0.05 within an error limit of one standard deviation.

Using our monitoring system, we have calibrated three independent fission chambers KNT-8 placed in the Pb-converter. The intensity of the proton beam as a function of the successive numbers of acceleration cycles is depicted in fig.5. The absolute calibration of the fission chambers makes it possible to monitor the primary beam of accelerated particles and nuclei of any intensity. Taking into account the mean time of neutrons slowing down to their capture in the converter and the stability of the characteristics of the used fission chambers [5], the results of the measurements are also independent of the time structure of a beam.

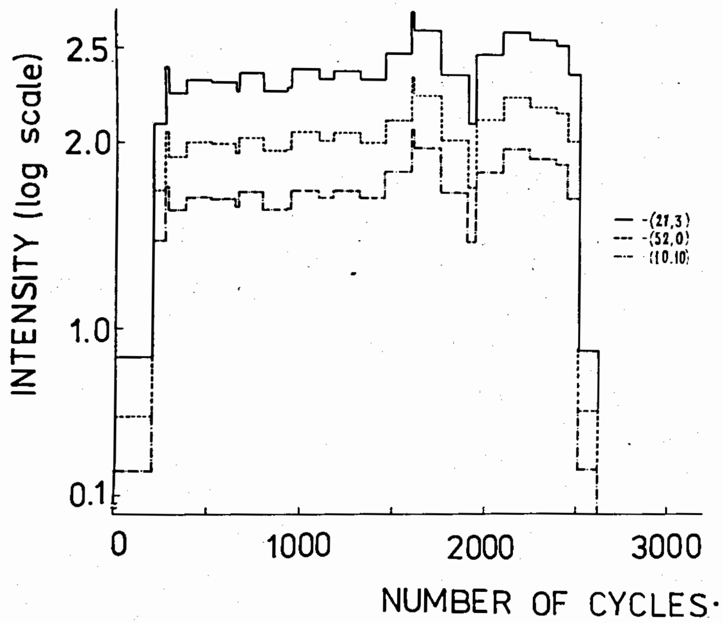

Fig.5. Intensity of the beam of protons as a function of time obtained from counts of the fission chambers KNT-8 calibrated by means of rotating nuclear emulsion. The measurements have been performed with three independent chambers placed in the Pb-converter with space coordinates (Z,R) = (27,3) , (52,0) , and (10,10), respectively.

3. MEASUREMENTS OF CROSS SECTIONS OF MONITORING REACTIONS

The above monitoring system has been used to measure the total cross sections of the reactions $^{27}Al(p,X)^{24}Na$ and $^{27}Al(^{12}C,X)^{24}Na$ at 3.65 A GeV by means of the well-known foil activation technique [6] and Ge(Li) gamma-ray spectroscopy. The advantage of aluminium foils as monitors of the beam flux is connected with the formation of ^{24}Na having a pertinent half-life (15.02 hours) and fractional abundances of gamma-rays at energies of 1368.5 keV and 2754.0 keV [7], respectively, which facilitates substantially measurements and data analysis.

The $^{27}Al(p,X)^{24}Na$ and $^{27}Al(^{12}C,X)^{24}Na$ cross sections at 3.65 A GeV were determined on the basis of ^{24}Na induced activities in the pure aluminium foils (99.99%) 6.5, 13.0 and 19.5 mg/cm^2 in thick, respectively. The guard aluminium foils of the same thicknesses as the Al-targets were used to eliminate recoil activities. The total beam flux of ^{12}C-ions and protons measured by means of the calibrated fission chambers was determined with an accuracy of better than 5%.

The appropriate aluminium target foils were gamma-ray counted on the Ge(Li) spectrometer with a 4096 channel capacity. The resolution of the Ge(Li) detector with a 45 cm^3 volume was about 3.0 keV at 1332.5

keV. The number of radionuclides in the irradiated target was determined using the standard formula [8]:

$$N_0 = \frac{\lambda t_1}{(1-e^{-\lambda t_1})e^{-\lambda t_2}} \cdot \frac{S_0}{(1-e^{-\lambda t_3})S_i} A_i t_i \,, \qquad (4)$$

where t_1, t_2 and t_3 are the periods of irradiation, waiting and counting, respectively ; t_i is the period of counting a standard gamma-ray source ; λ is the disintegration constant of ^{24}Na ; S_0 and S_i are the photopeak area of the characteristic gamma-ray of the radionuclide formed in a target foil and a standard gamma-ray source, respectively ; and A_i is the activity of this source. **Figure 6 illustrates an induced** activity gamma-ray spectrum of the aluminium foil irradiated with 3.65 A GeV ^{12}C-ions. The cross sections have been determined from the most intense gamma-ray line at 1368.5 keV. The photopeak area of the most intense line of the ^{24}Na was compared with that of the standard gamma-ray source of ^{60}Co at 1332.5 keV. The appropriate areas have been determined with uncertainties of better than 5%. It should be noted that the gamma-ray spectra of both samples have been measured with identical geometry. Taking these facts into account, the differences between efficiencies at 1368.5 keV (^{24}Na) and 1332.5 keV (^{60}Co) can be neglected.

The weighted average cross sections for $^{27}Al(p,X)^{24}Na$ and $^{27}Al(^{12}C,X)^{24}Na$ are 8.7 ± 0.8 mb and 19.0 ± 1.5 mb.

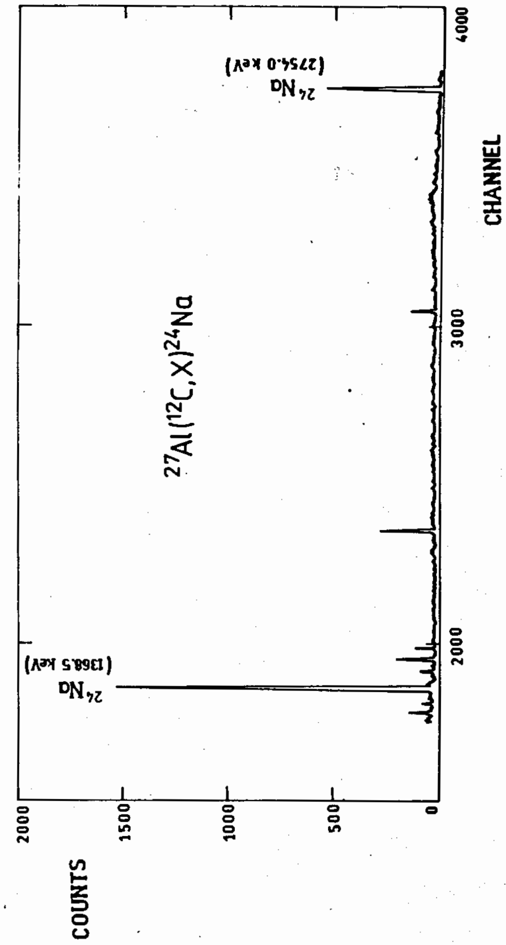

Fig.6. Gamma-ray spectrum from the aluminium target irradiated with 3.65 AGeV ^{12}C-ions taken with the 45 cm^3 Ge(Li) detector.

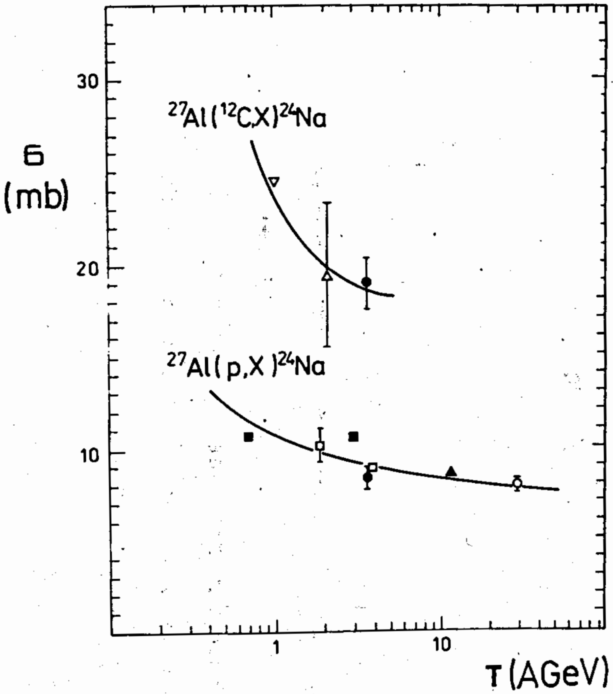

Fig.7. Dependence of the total cross sections of the monitoring reactions $^{27}Al(^{12}C,X)^{24}Na$ and $^{27}Al(p,X)^{24}Na$ on the energy of projectiles. □ - Cumming [3]; △ - Porile et al. [9]; ▽ - Lund [10]; ■ - Crespo et al. [11]; ▲ - English et al. [12]; ○ - Cumming et al. [13]; ● - present measurements.

The latter value corresponds to 19.4 ± 3.9 mb and 24.5 mb for $^{27}Al(^{12}C,X)^{24}Na$ at 2.1 A GeV[9] and 1.0 A GeV[10], respectively. The cross section for $^{27}Al(p,X)^{24}Na$ at 3.65 GeV correlates with those measured over the energy range from 0.7 to 28.0 GeV [3,11-13]. The experimental cross sections of both monitor reactions as a function of projectile energy are compared in fig.7.

4. CONCLUSIONS

The new experimental technique developed for monitoring beams of relativistic projectiles accelerated at the Dubna synchrophasotron unifies beam flux measurements. It is also suitable for both continuous and pulsed regimes of acceleration over a wide range of energies and intensities. The advantage of the method is the possibility to gain a real profile of the beam. Moreover, the monitoring system, placed after the experimental apparatus, does not affect the experimentally studied interaction. It should be noted that at the first step of beam flux monitoring a thin rotating layer of nuclear emulsion is placed over a short period at the beam entrance while neutrons are recorded in the Pb-converter positioned after the experimental apparatus. A comparison between the appropriate counting rates yields the calibration curve. Then, the absolute monitoring of a beam during a real experiment can be provided from the counting of neutrons only. It may be also interesting that our technique does not require any special-purpose electronics as well as the identity of the used fission chambers or other detectors of secondary particles. This makes possible calibrating other monitoring systems which has been also demonstrated. In addition, the precise measurements of the beam flux of 3.65 A GeV ^{12}C-ions and protons enable one to determine the total cross sections of the monitoring reactions $^{27}Al(p,X)^{24}Na$ and $^{27}Al(^{12}C,X)^{24}Na$ with a sufficient accuracy for beam flux monitoring by the simple activation technique.

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