CHARGED PARTICLES FROM THE CAPTURE OF NEGATIVE MUONS BY THE NUCLEI ^{28}Si, ^{32}S, ^{40}Ca, AND ^{64}Cu

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A mass identification is carried out of the charged particles emitted upon absorption of negative muons by the nuclei ^{28}Si, ^{32}S, ^{40}Ca, and ^{64}Cu. The proton energy spectra and emission probabilities are calculated for protons at energy higher than 15 MeV and for deuterons at energy higher than 18 MeV. The obtained energy spectra extend to 50 MeV, and the fraction of the deuterons in the total number of charged particles increases with decreasing charge of the nucleus. Depending on the charge of the nucleus, the probability of proton emission has a maximum in the calcium region.

A study of particles emitted upon absorption of negative muons by nuclei is greatest from the point of view of the study of the structure of the nucleus and the mechanisms whereby muons are captured by nuclei. The latest experimental [1] and theoretical [2] data show that the resonant mechanism of muon capture [3] predominates at low emitted-particle energies. As to the region of high energies, the situation here is unclear. Apparently, processes of direct capture of muons by correlated nucleon pairs begin to predominate at high energies.[4, 5] From general considerations, one can assume here that the processes leading to emission of high-energy protons and neutrons have much in common. For a complete understanding of the physical nature of the processes of absorption of muons by complex nuclei, it is necessary to have information both on the emission of the neutrons and on the emission of the charged particles.

Experimental data on the emission of charged particles, particularly at high energies, are quite skimpy and incomplete. The first investigations were carried out by Morinaga and Fray [6] on heavy emulsion nuclei. They have shown that the emission of charged particles is strongly suppressed compared with the emission of neutrons, and amounts to only 3% of the total capture probability. The data obtained by these authors on the emission of protons and α particles cannot be reconciled simultaneously with the theoretical calculations performed by Ishii [7] on the basis of the statistical model. To explain the hardness of the energy spectrum and the large proton yield in the indicated experiment, Singer [4] proposed a mechanism for the capture of muons by two-nucleon clusters localized in the surface layer of the nucleus. Such an analysis has made it possible, to some degree, to obtain agreement with experiment, but it should be noted that the reliability of this analysis is very small, in view of a large number of additional assumptions, most of which cannot be directly verified experimentally and are very difficult to justify theoretically.[8]

A common shortcoming of the preceding experiments [9–13] is that the procedure employed has made it possible to identify the charged particles by masses only in a limited manner, or not at all; this can be strongly reflected in the accuracy of the interpretation of the experimental data. In addition, in the case of charged particles of high energy, there are practically no data on muon capture by nuclei having definite values of the nuclear charge.

All the foregoing points to the importance of a consistent experimental study of the hard parts of the spectra of the charged particles emitted upon absorption of negative muons by complex nuclei. The purpose of the present study was to measure the energy spectra and the emission probabilities of the protons, deuterons, and tritium nuclei with energy larger than 10 MeV following muon capture by several nuclei in the nuclear-charge range $10 < Z < 30$.

ORGANIZATION OF EXPERIMENT AND EXPERIMENTAL SETUP

We were faced with the following tasks:

a) Separation of the charged particles by masses;

b) measurement of the absolute energy spectra of the protons, deuterons, and tritium nuclei, starting with the lowest possible energies;

c) determination of the dependence of the yields of these particles on the nuclear charge.

To separate the charged particles by masses m we employed the method of simultaneously measuring the ionization loss dE/dx in a thin counter and the total energy E in a thick counter. It is known that

$$E(dE/dx) \sim mZ^2$$

independently of the energy. The most suitable detectors for the measurement of the ionization loss of charged particles are thin surface-barrier silicon de-

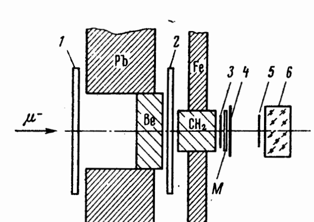

FIG. 1. Block diagram of setup: 1–6–counters, T–target.

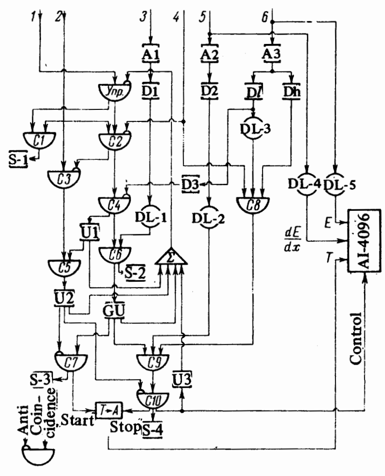

FIG. 2. Simplified block diagram of the electronic circuitry: A–amplifier, D–discriminator, C–coincidence circuit, DL–delay line, S–scaler, U–univibrator, Σ–adder, T → A–time-amplitude converter.

tectors, since they exhibit no effects of signal saturation with increasing ionization density. To measure the total proton energy in the interval up to 100 MeV, it suffices to use the crystal CsI(Tl).

The measurements were performed on the nuclei ^{28}Si, ^{32}S, ^{40}Ca, and ^{64}Cu. The work was performed in the meson channel of the JINR synchrocyclotron. We used in the experiment a beam of negative muons with momentum 96 MeV/c. Figure 1 shows a block diagram of the setup, and Fig. 2 a simplified block diagram of the electronic circuitry.

Counters 1 and 2 measured 10 × 10 × 1 cm (scintillating plastic), and counter 4 measured 4 × 4 × 0.03 cm (scintillating plastic); counters 3 and 5 were silicon surface-barrier detectors with area 5.3 cm^2 and thickness 50 mg/cm^2. Counter 5 served to measure the ionization loss dE/dx of the charged particles. The detectors had a resolution of 50 keV for α particles with energy 5.5 MeV. The total energy E was measured with a spectrometer based on a CsI(Tl) crystal with dimensions 4.0 (diam.) × 2.2 cm, which was scanned with an FÉU-13 photomultiplier (counter 6). The spectrometer energy resolution was 10.5% for γ quanta from Co^{60}. Targets of thickness ~0.15 g/cm^2 were located at a distance of 2.65 cm from counter 5, which set the solid angle of the apparatus. The telescope made up of counters 3–6 and the target were placed in a vacuum.

The incident muon beam (coincidences 12, circuit C1) was decelerated with beryllium and polyethylene filters. To decrease the number of stopped muons in counter 3, the latter was made thin (50 mg/cm^2). The discrimination of the pulses in counter 3 (circuit D1) has made it possible to select those muons whose ionization losses were close to those corresponding to complete stoppage in the target. Counter 6 (discriminator Dl, threshold 1 MeV) suppressed, in addition to counter 4, the transiting muons of the beam (prompt coincidences $12\bar{4}6$, circuits C2 and C4). Stoppage of the muons in the target (coincidences $123\overline{46}$, circuit C6) triggered the gate univibrator GU. The gate duration (10–2 μsec) was chosen with allowance for the lifetime of the muons in the investigated target. Under the operating conditions, we had 30 stoppings per second. The charged particles (coincidences 456, circuit C8) were registered during the time of duration of the gate pulse (circuit C9). The time of emission of the charged particles relative to the stopping of the muon was determined with the aid of a time-amplitude converter (circuit T → A). The delays in the electronic circuitry were chosen such that the zero time reading occurred at ¼ of the way into the gate pulse.

If a second muon entered the apparatus during the time of the gate pulse (circuit C5, univibrator U1), then univibrator U2 blocked the registration of the stopping itself (circuit C5) and the signal for external control of the analyzer (circuit C10).

The three-dimensional spectrum of the events (the charged-particle energy, its ionization loss, and the emission time) were registered in the memory of the AI-4096 analyzer of the Measurement Center of the Nuclear Problems Laboratory.[14] Each measured quantity was allotted 256 channels.

CALIBRATION OF SPECTROMETER ON THE BASIS OF CsI

The spectrometer based on the CsI crystal was calibrated with the proton channel of the synchrocyclotron. The protons and deuterons were produced by irradiation of a beryllium or uranium target with the primary beam of the extracted protons. The required proton and deuteron energy was set by the field of the deflecting magnet or by the thickness of the absorber. In the calibration we also used a silicon detector, making it possible to register separately the protons and deuterons in the beam. The two-dimensional spectrum of the events (energy, ionization losses) was recorded with the aid of an AI-4096 analyzer. 256 channels were assigned to each quantity.

Figure 3 shows one of the two-dimensional spectra obtained at a fixed charged-particle momentum. To the left and below, the same figure shows respectively the spectrum of the ionization loss, obtained with the silicon detector, and the energy spectrum, obtained with the CsI spectrometer. The first peak in the low-energy region on the energy spectrum (E scale) is due to the presence in the beam of π^+ mesons with the same momentum as the protons. The second peak is due to the deuterons and the third to the protons.

Calibration measurements made at different proton and deuteron energies have shown that the protons and deuterons have the same light yield from our CsI(Tl) crystal in the investigated energy interval, within an error of 5–10%. The energy resolution of the spectrometer was ~5% for protons with energy ~60 MeV.

DATA REDUCTION

All the obtained information was processed with the BESM-6 computer of our institute. Figure 4 shows one of the characteristic two-dimensional particle spectra obtained directly during the measurements. It is easy to see that all the points form three basic tracks. The lower track corresponds to the transiting muons and the decay electrons, the middle one to the protons, and the upper one to deuterons. Figure 5 shows one of the obtained charged-particle mass spectra. The spectrum

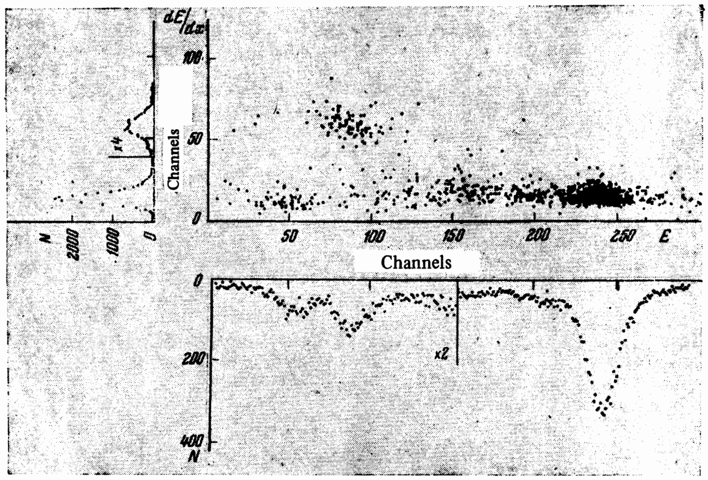

FIG. 3. Distribution of charged particles by ionization loss and by total energy, obtained at a momentum 390 MeV/c from calibration measurements. Left–ionization-loss spectrum, below–energy spectrum.

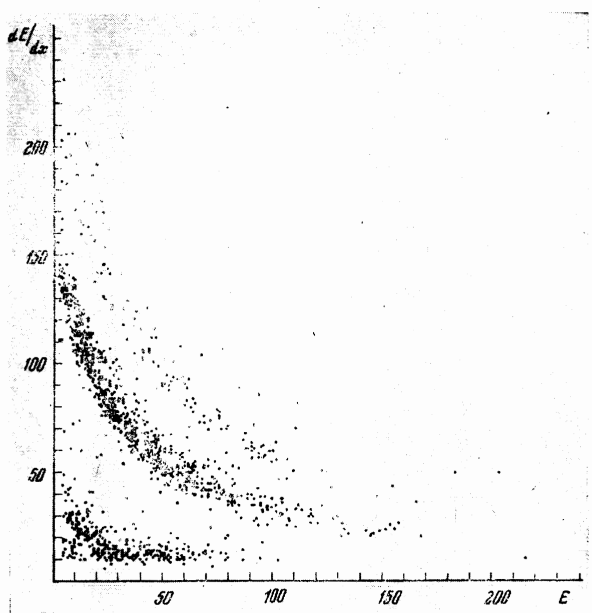

FIG. 4. Distribution of charged particles with respect to the ionization loss (dE/dx) and the total energy (E) for ^{40}Ca (E and dE/dx are expressed in terms of analyzer channels).

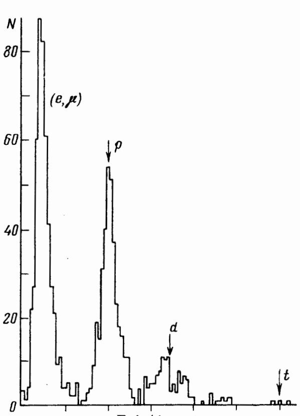

FIG. 5. Mass spectrum of charged particles for ^{28}Si (the abscissas represent EdE/dx).

shows clearly three peaks corresponding to the three tracks in Fig. 4, in the same sequence. Several counts at the edge of the spectrum are interpreted by us as tritium nuclei. The arrows on the spectrum indicate the positions of the peaks.

After separating the charged particles by masses, we reconstructed individually the total energies of the protons, deuterons, and tritium nuclei, with account taken of the energy losses in the target and in counter 4.

In the background measurements, to maintain the same total amount of matter on the particle paths, the targets were placed between counters 4 and 5. Measurements without the targets have shown that the remaining charged-particle count is due to stoppings of muons and their subsequent capture in the silicon detector (counter 3). This has enabled us to dispense with subtraction of the background in the energy spectrum for ^{28}Si. For the remaining targets, the background was accounted for by subtracting the spectrum for ^{28}Si, normalized to the number of counts without a target and obtained in the corresponding series of measurements, from the measured energy spectrum.

The reduction of the events was facilitated by the fact that, as shown by an analysis of the temporal spectra, there was no background of random coincidences. The temporal analysis began ~50 nsec after the stopping of the muons in the target. This was taken into account in the determination of the probability of the emission of the charged particles, in the form of a correction factor. The experimentally obtained lifetimes of the muons on the investigated nuclei are in good agreement with the generally-accepted values.

Energy spectra of protons and deuterons

E, Mev	Silicon		Sulfur		Calcium		Copper	
	N_p	N_d	N_p	N_d	N_p	N_d	N_p	N_d
11	94±10		83±10		113±12		29±7	
14	134±12	21±5	190±15	7±4	132±13	13±4	53±9	5±3
17	109±10	36±6	128±12	36±7	95±11	20±5	30±7	7±3
20	89±9	47±7	65±9	24±6	68±9	6±4	28±6	1±3
23	50±7	33±6	60±8	35±7	52±8	12±5	9±4	2±3
26	47±7	18±4	44±7	13±4	37±7	12±4	17±5	5±3
29	27±5	10±3	31±6	13±4	27±6	11±4	6±3	3±2
32	21±5	11±3	19±5	8±3	17±5	3±2	9±3	4±2
35	15±4	12±4	16±4	7±3	14±4	14±4	5±3	1±2
38	12±4	7±3	8±3	7±3	11±4	7±3	11±3	
41	12±4	5±2	8±3	7±3	5±3	1±1	2±2	
44	6±2	2±1	4±2	3±2	5±3	3±2	1±1	2±1
47	1±1	2±1	6±3	2±1	2±1		4±2	1±1
50	7±3	4±2	1±1		4±2		1±1	
53		1±1	4±2		3±2	1±1	1±1	
56			2±1		1±1	1±1	1±1	1±1

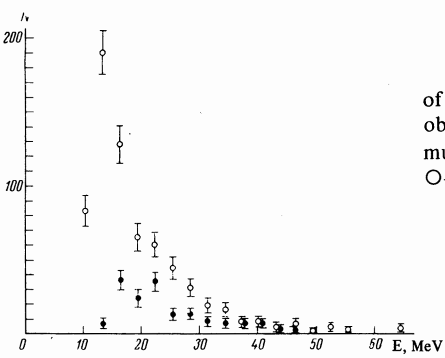

FIG. 6. Energy spectra of protons and deuterons obtained upon capture of muons by ^{32}S nuclei: O–protons, ●–deuterons.

EXPERIMENTAL RESULTS

Figure 6 shows the measured energy spectra for protons with energy higher than 15 MeV and deuterons with energy higher than 18 MeV, obtained by capture of muons by ^{32}S nuclei. The energy spectra of the protons and deuterons obtained from the other targets have a similar character and are listed in the table. The decrease in the number of protons with energy lower than 14 MeV and of deuterons with energy lower than 16 MeV is due to their absorption in the telescope. The errors indicated in the spectra are statistical. The main energy uncertainty for protons with energy up to 20 MeV is introduced by the scatter of the ionization losses in the target ($\leq \pm 0.8$ MeV), and at high energies by the resolution of the CsI spectrometer ($\leq \pm 1.4$ MeV).

To obtain the differential proton- and deuteron-emission probabilities in a 1-MeV interval it is necessary to multiply the data for the energy spectra by suitable coefficients, whose values are 0.73×10^{-5}, 0.96×10^{-5}, 1.27×10^{-5}, and 1.60×10^{-5}, for ^{28}Si, ^{32}S, ^{40}Ca, and ^{64}Cu, respectively.

In view of the small statistics obtained for the tritium nuclei, we present only estimates of the integrated probabilities of emission of tritium nuclei from the investigated targets:

Target:	Silicon	Sulfur	Calcium	Copper
$W(E > 24\,\mathrm{MeV}) \cdot 10^4$:	0.7±0.4	0.3±0.3	<0.7	0.5±0.5

Figure 7 shows the integral probabilities of the emission of protons, deuterons, and charged particles per capture act at different threshold energies, as a function of the target-nucleus charge. The smooth curves in the figures join, for clarity, the corresponding experimental points. Figure 7c shows the results obtained by the Vaĭsenberg group[13] for charged particles with energy larger than 25 MeV on heavy emulsion nuclei (Z = 41).

The absolute yield of the protons (Fig. 7a) as a function of the charge of the nucleus has a maximum in the region Z = 20. At energies higher than 15 MeV, the proton yield changes from $(8.8 \pm 0.6) \times 10^{-3}$ for ^{28}Si to $(13.0 \pm 1.1) \times 10^{-3}$ for ^{40}Ca, where a maximum is reached, and then decreases rapidly to $(6.0 \pm 0.7) \times 10^{-3}$ for ^{64}Cu.

The absolute yield of the deuterons (Fig. 7b) at energy larger than 18 MeV increases with decreasing nuclear charge from $(1.0 \pm 0.3) \times 10^{-3}$ for copper to $(3.3 \pm 0.3) \times 10^{-3}$ for silicon.

It is interesting to note that for the soft part of the spectrum a number of papers[6, 10, 15] give for the yield of the charged particles following capture of muons by nuclei with small Z (Z = 5–10) a value much higher than for nuclei with large Z (Z = 35–50).

Figure 8 shows the relative yields of the protons and deuterons as percentages of the total yield of charged particles for energies higher than 18 MeV. One can see that the fraction of the deuterons in the total number of charged particles increases monotonically with decreasing nuclear charge, from (17 ± 4)% for ^{64}Cu to (34±2)% for silicon. A similar dependence was observed for energies 5–25 MeV by Vaĭsenberg et al.,[10] who estimated the fraction of the deuterons and tritium nuclei in the total number of charged particles at ~15% for heavy emulsion nuclei and ~50% for light emulsion nuclei.

Figure 9 shows the total energy spectrum of charged particles due to the capture of negative muons in silicon. In the interval 0–26 MeV, the spectrum was taken from [12]. At energies higher than 18 MeV, the spectrum is represented by our data, normalized to the number of stopped muons in [12]. In the overlap region (18–26 MeV), there is qualitative agreement between both results.

We are presently carrying out a detailed analysis of the obtained experimental material and the results will be published later.

In conclusion, the authors are deeply grateful to V. V. Avdeĭchikov and O. V. Lozhkin for preparing the silicon detectors, to V. N. Komarov and O. V. Savchenko for help with the calibration measurements, to S. S. Gershteĭn and R. A. Éramzhyan for useful discussions,

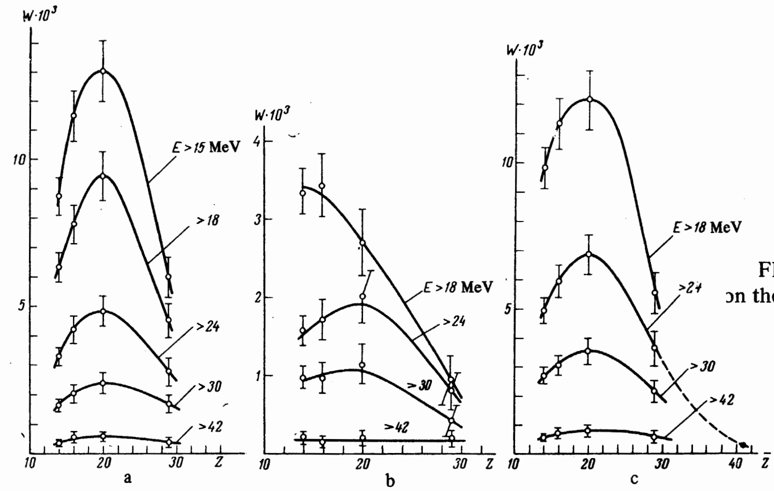

FIG. 7. Dependence of the integral probability of particle emission on the nuclear charge: a—protons, b—deuterons, c—charged particles.

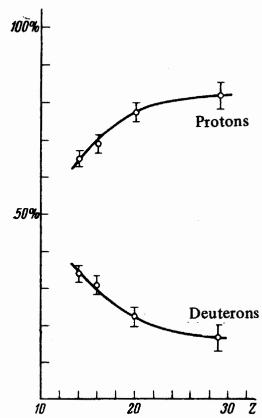

FIG. 8. Dependence of the proton and deuteron yields on the nuclear charge as a percentage of the total yield of charged particles.

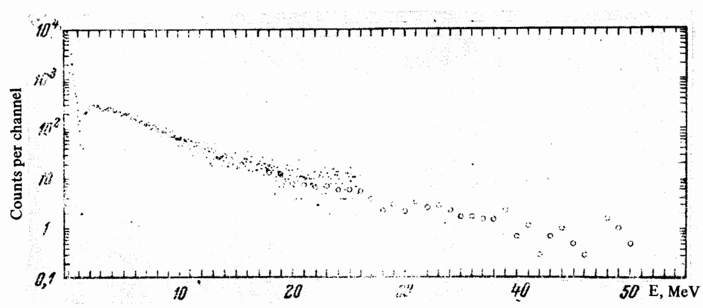

FIG. 9. Total energy spectrum of the charged particles following the capture of negative muons by ^{28}Si nuclei: points—spectrum taken from [12], circles—spectrum obtained in the present investigation.

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