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INVESTIGATION OF β-DELAYED NEUTRON EMISSION AND ELASTIC SCATTERING OF NEUTRON-RICH ISOTOPES OF He AND Li

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Experiments on synthesis and investigation of properties of new neutron-rich nuclei of light elements are carried out at some scientific centres of heavy ion physics |1-4|.

Such investigations pursue two goals:

- investigation of the properties of a wide variety of nuclei lying near neutron drip line,

- identification of nucleon stability (or instability) of these nuclei.

The synthesis and investigation of properties of neutron-rich nuclei present a great interest not only for nuclear physics but also for astrophysics (for explanation of nucleon synthesis and stars evolution).

The main difficulties in the realization of experiments on obtaining neutron-rich nuclei are due to their small yeild. These difficulties can be overcome with increasing intensity and beam energy of heavy ions and with designing a set-up separating secondary beam formation from corresponding products of nuclear reactions.

One of the methods to obtain secondary beams is the fragmentation reactions and multinucleon transfer reactions at energies of $\sim$ 20 MeV/nucl.

In the present report the results of the works studying the properties of neutron-rich nuclei of He and Li at secondary beams of a cyclotron of the Laboratory of Nuclear Reactions JINR (accelerator U-400) and set-ups designed |5| for these purpose are presented.

The main components of the set-up are:

- magnetic separation channel

- system of detectors for nuclear identification and studying of their properties

-. electronics, maintaining this system of detectors and the set-up.

EXPERIMENTAL PROCEDURE

1. Magnetic separator MT-1MT-2

The schematic view of the experimental set-up for separation and identification of nuclear reaction products is presented in fig. 1. The

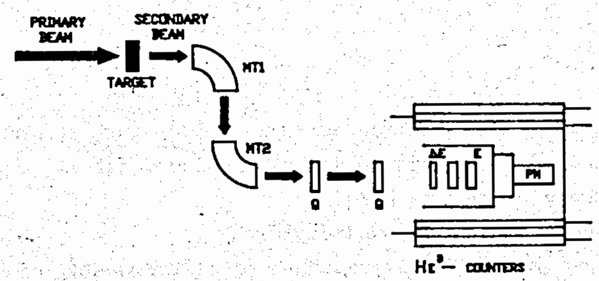

Fig. 1. Scheme of experimental set-up.

primary beam of heavy ions from the accelerator U-400 focussed on and bombarded the water cooled target T the thickness of which was calculated for total absorption. The separation of light reaction products is achieved by an ion-optical system for transportation and separation of the beam on the cyclotron which includes a quadrupole lens (Q) and dipole magnets MT1 and MT2. The products produced and emitted at angle 0° are separated by A/Z^2 in MT1. The second magnet MT2 is used for dispersion compensation. Such system is double achromatic – both in angle and position. The maximum magnetic rigidity of such a separator equals 1.5 Tesla·m and the solid angle is about 10 msterad. For better separation it is planned to set slits and an additional stripper foil between MT1 and MT2 like at the LISE-set-up |6|. The quadrupole lens at the MT2 exit is used for transportation of the secondary beam and its focussing onto a telescope for identification and investigation of characteristic of exotic nuclei decay.

One should note, that the intensity of the secondary beam and the ratio of particles yield from the target depend on Z nucleus-target and selected magnetic rigidity of the MT1-MT2 system. In reactions with ^{11}B ions (20 MeV/nucleon) and targets from ^{12}C and ^{9}Be the yield of ^{4}He and ^{6}He isotopes is predominating. The measured yields ratio of ^{6}He at bombardment of ^{11}B targets with ^{181}Ta, ^{12}C and ^{9}Be is near to 1:2:4 ratio. The widest range of secondary products is oberved in reactions with heavier targets and ions, for example, ^{20}Ne (20 MeV/nucleon) + Ta (fig. 2). The

efficiency of separation of secondary beams can reach several per cent from their total yield in the given solid angle.

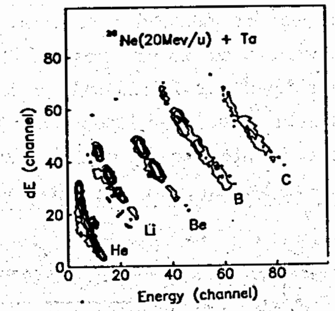

Fig. 2. ΔE-E-matrix for reaction ^{20}Ne (20 MeV/nucleon) + Ta

2. ΔE-E telescope and identification of reaction products

In order to analyse the isotopic purity of secondary beams after the magnetic separator MT1-MT2 the method of specific losses and total energy measurement was used. A semiconductor telescope applied for this goal includes two solid state ΔE-detectors with a thickness of 40-50 μ and E-detector with a thickness of 2 mm. Registered particles are identified by means of the image point on the matrix corresponding to coded amplitudes of ΔE- and E-pulses. From the matrix presented in fig. 2 it follows that telescope resolution allows to identify correctly the reaction products by A and Z.

3. β – particles detector

For registration of β-particles, emitted from implanted nuclei into the semiconductor telescope, a scintillator of NE-213 type in the form of a cylindrical glass with a bottom was applied. The dimensions of the scintillator are 100 x Ø 50 mm², the walls thickness is 5 mm. The bottom of the scintillator is optically bound with a photomultiplier PEM-93. As it was shown by the results of measurements, the efficiency of β-particles registration at energies typical for β-decay of neutron-rich isotopes of light elements, approaches 95%. A signal from the PEM proceeded after amplification to the amplitude-code converter, the linear gates of which opened after the permissive signal of fragment registration with selected A and Z the properties of which are investigated.

4. Neutron detection and measurement of their multiplicity

Proportional counters filled with ^3He with 1% CO_2 admixture at a pressure of 7 atm were chosen as neutron detectors. In the given set-up 56 proportional counters were used which were positioned in 4 rows by 14 counters in a cylinder made of plexiglass with a volume of about 0.2 m^3 and a cavity inside for a semiconductor telescope and ß-particles detector.

The scheme of neutron counter position is given in fig. 3 and the detailed description is presented in ref. |7|. The angle between counters

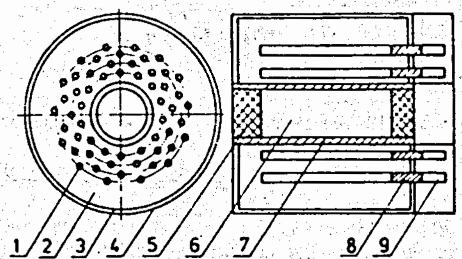

Fig. 3. Scheme of neutron counters position with ^3He-filling: 1 – ^3He-counters; 2,7,8 – plexiglass; 3 – cadmium foil; 4 – steal tube; 5 – plexiglass plugs; 6 – cavity for detectors; 9 – preamplifier and high-voltage scheme.

is 12°. The electronic system used for neutron detector maintenance permits to obtain information about the quantity and numbers of counters which registered the neutrons.

The detection efficiency of single neutrons $\mathcal{E}_n$ was determined relative to the ^{248}Cm standard for which the mean value of prompt neutrons per one event of spontaneous fission $\bar{\nu} = 3.14 \pm 0.001$ was taken. At the same time the efficiency was $\mathcal{E}_n = 0.315 \pm 0.010$. Emission probabilities of different neutron numbers P_i are related with experimentally measured distribution over multiplicity of the registered events by a system of equations:

$$\sum_{i \geq n}^{n_{max}} \frac{i!\,\varepsilon_n^n (1-\varepsilon_n)^{i-n} P_i}{n!\,(i-n)!} = F_n ,$$

with normalization condition: $\sum_{i=0}^{n_{max}} P_i = 1$;

where $F_n = \frac{N_n}{\sum_{i=0}^{n_{max}} i\, N_i}$,

and N_i – events number with i – registered neutrons.

In order to determine P_i values and their errors, the method of statistical regularization |8| was employed.

5. System of data acquisition

A block-scheme of electronic system of the given set-up is presented in |5|. The process of experimental data acquisition is realized by means of a PS/AT computer and proceeds in the following way. After measuring the specific stopping power losses Δ E and the rest energy E, the data selection over given value of A and Z for a short period (tens of µs) by the analysis of applying the registered event to the internal region of a preassigned ΔE-E contour on the matrix is performed. In case of fragment registration, the properties of which are investigated, the permission signals proceed to ß-particles and neutron registrations. The time of arrival of ß-particle is measured. At the same time the maximum expectation time of ß-particle equals a few half-lives. Beside the starting signals of ß-n correlations, simultaneously with them, a signal locking the HF-generator of the U-400 cyclotron is formed. One should note, that the time from the registration of the fragment moment on the telescope up to the locking of the HF-generator of the cyclotron is essentially lower than the time-interval between successive clots of accelerating ions. In case a signal from the ß-counter into the computer memory is absent the information enters only from the semiconductor telescope. In case there apprears a signal from a ß-particle during n $T_{1/2}$ the information is added by the time of arrival code, the amplitude of ß-signal and data about the registered neutrons.

RESULTS AND ANALYSIS OF EXPERIMENTAL DATA BY ß – HALF-LIFE AND ß-n DELAYED NEUTRON DECAYS OF LIGHTEST NUCLEI

On a separated secondary beam of the U-400 accelerator experiments investigating the properties of ß – decay of ^8He, ^9Li, ^{12}Be, ^{13}B were carried out and preliminary data on ß-n decay of ^{11}Li were obtained. The secondary beam of ^8He and ^9Li was obtained in reaction ^{11}B (20 MeV/nucleon) + + ^{181}Ta, and for producing ^{12}Be and ^{13}B nuclei the reaction with ^{20}Ne ions and energy (20 MeV/nucleon) seemed to be optimal. As an illustration of this in fig. 4 the distribution of ß – particles corresponding to the investigated nuclei decay are presented. For He and Li isotopes the interruption time of secondary beam for ß – particle waiting for was 1 sec

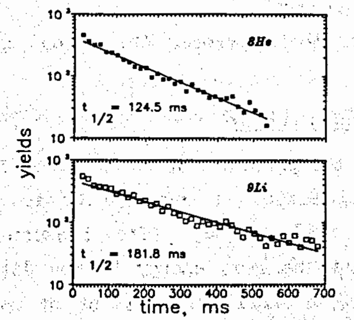

Fig. 4. Experimental curves of nuclear decay of ^{8}He and ^{9}Li.
Straight lines present a fitting of experimental data by the least squares method.

and for Be and B – 100 msec, respectively. As follows from table 1, the obtained values of half-life ($T_{1/2}$) are in a good agreement with the previously measured values, with the exception of ^{12}Be.

Table 1.

Nucleus	$T_{1/2}$(ms) exp.	$T_{1/2}$(ms) other works		P_n, W_n^* (%) exp.	P_n, W_n^* (%) other works	
^{8}He	124.5± 0.2	119±1.5	|10|	P_0 =87.0±1.1	P_0 =84±1	|10|
				P_1 =12.7±2.6	P_1 =16±1	|10|
^{9}Li	181.8±0.4	178.3±0.4	|10|	P_0 =86.6±0.9	W_n =50±4	|10|
				P_1 =13.3±3.4		
^{11}Li	8.0±1.0	8.5±0.2	|10|	P_0 =45.9±4.6		
				P_1 =29.4±2.6	P_1 =85±1	|11|
				P_2 =15.2±3.0	P_2 =4.1±0.4	|11|
				P_3 =5.1±3.0	P_3 =1.9±0.2	|11|
				W_n =94±9	W_n =95±8	|11|
^{12}Be	13.1±0.5	11.4±0.5	|9|			
		23.6±0.9	|10|	W_n < 0.08	W_n ≤ 1	|10|
^{13}B	17.0±0.4	17.4±0.2	|10|	W_n < 0.03	P_0 ≃ 100	|10|

*The definition of $W_n = \sum i P_i$ is given elsewhere |5|.

The obtained value clearly conforms with $T_{1/2}$=11.4 ms measured in paper |9|.

Besides half-life measurements the present detection system allows to measure multiplicity distributions of neutron emission and also angular distributions of neutrons at different multiplicity. In table 1 the probabilities of ß-delayed neutron emission for investigated nuclei are given. The data analysis shows, that P_n probabilities of ß-delayed neutron emission for ^{8}He isotope conform with table values |10|.

For ^{12}Be and ^{13}B decay the neutron emission was not observed, which permits to obtain the limits which do not contradict to the known data |10|. As to ^{9}Li, we have received a smaller value of neutron emission probability compared with that in |11|. Note that data on multiplicity distribution of neutron emission for ^{11}Li disagree with the results |10|, though the experimental values of W_n are in good adreement. The cause of such disagreements is not yet determined. These uncertainties require additional experiments on precise determination of properties of neutron-rich isotopes.

For nuclei of greater intensity in secondary beams such as, ^{8}He and ^{9}Li angular neutron distributions emitted after ß-decay are obtained. In fig. 5 the angular distribution spectra are presented. From spectra analysis one should make a conclusion about isotopic neutron distribution at n = 1. The experiments on studying the angular correlation between ß-delayed neutrons in case of multiple emission are of great interest

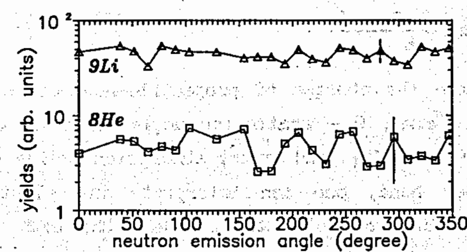

Fig. 5. Angular distribution of neutrons emitted after ß-decay of ^{8}He and ^{9}Li nuclei.

and should be continued. The other trend in the works on the lightest nuclei properties is the investigation of ß-delayed emission of d,t-clusters and α-particles and other still heavier nuclei.

STUDY OF ELASTIC SCATTERING OF ^{6}He AND ^{9}Li NUCLEI ON ^{208}Pb

Rapid development of secondary beam technique offers a unique possibility to make spectroscopical studies of nuclei far from stability |12|. One of the main goals of such investigations is to study the interaction particle cross section of the secondary beam with target nuclei. One of the most interesting results obtained in such experiments is the radius of interaction of light neutron-rich nuclei from systematic analysis of total reaction cross sections measured at high and intermediate energies of secondary particles |13, 14|. Nevertheless one should note, that data on reaction cross sections are rather insensitive to the details of nucleon distributions in peripheral region and in the interaction potential between the colliding ions |15|.

Earlier, another method |16| of nuclear structure investigation, based on applying the classical interpretation of heavy ions interaction with nuclei at ion energies above the Coulomb barrier was proposed and developed. According to this approach a particle moves along the Coulomb trajectory and can undergo inelastic interaction deducing it from the channel of elastic scattering. Studying the dependence of experimental data on elastic scattering from the distance of closest approach

$$D = \frac{a}{2}\left(1 + \sin^{-1}\left(\frac{\theta}{2}\right)\right) \qquad (1)$$

where $a = \frac{Z_t Z_p e^2}{E}$

($Z_p \cdot e$ and $Z_t \cdot e$ are the charges of projectile-nucleus and target-nucleus, E – energy ion in c.m., θ – scattering angle in c.m.) one can determine both interaction radius |16|, and strong absorption radius |17|.

On the other hand, one can interprete the elastic scattering of heavy ions in the framework of optical model (OM) both with a phenomenological optical potential (OP) and semimicroscopical real part calculated |18| from nucleon-nucleon interaction and nucleon distributions in colliding nuclei.

The experiments on angular distributions research of elastic scattered nuclei ^{6}He and ^{9}Li on nuclei from ^{208}Pb and their investigation with the help of the mentioned methods were carried out. ^{6}He and ^{9}Li nuclei obtained at bombardment of a thick target from tantalum by ^{11}B ions with energy of ~ 200 MeV |19|, were formed into secondary beam by means of

reduction system and extracted beam formation of U-400 |5| accelerator and via collimators system of 5 mm diameter with the help of a quadrupole lens were focussed on a thin target from separated isotope of ^{208}Pb of ~ 300 μg/cm² thickness. Separation system of reaction products was adjusted to ^{6}He emission with energy of 57 MeV and ^{9}Li with energy of 86 MeV and with energetic accuracy ~ 2%. The scattered nuclei ^{6}He and ^{9}Li on Pb-target were registered by plastics of CR-39 type. The monitoring of secondary beam was performed with the help of a telescope made of silicon semiconductor detectors: 2ΔE x E containing 2ΔE detectors with a sensitive layer from 70 up to 150 μm and an E-detector of 2-2.5 mm thickness placed in the centre of the plastic hole |9|.

After etching the plastic was scanned under microscope and the tracks of ^{6}He and ^{9}Li were identified by their diameters taking account the angular direction in relation to the secondary beam. In fig. 6 the elastic scattering

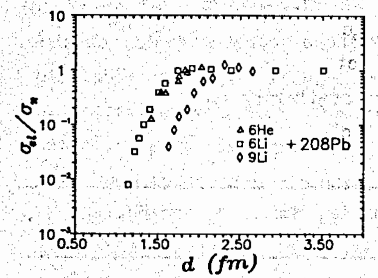

Fig. 6. The elastic to Rutherford cross section ratio as a function of distance of closest approach parameter for ^{6}Li (51 MeV), ^{6}He (57 MeV) and ^{9}Li (86 MeV) elastically scattered on ^{208}Pb.

differential cross section of ^{6}He, ^{6}Li and ^{9}Li on ^{208}Pb divided by the corresponding Rutherford one are given as a function of the D-distance of the closest approach more exactly as a function of $d = D/(A_t^{1/3} + A_p^{1/3})$, where A_t and A_p are the mass numbers of the target and the projectile, respectively. The data for ^{6}Li (E = 51 MeV) taken from ref. |20| are also shown. It is seen from the figure, that the ratio σ_{el}/σ_R undergoes the break at some values of d_o, which indicates to the beginning of a nuclear or another process of strong interaction that leads to the particles deviation from the Rutherford trajectory.

The determined in this way parameters d_o are given in table 2.

Table 2. Values of d_o parameter for elastic scattering of ^6He, ^6Li and ^9Li on ^{208}Pb

Reaction	Energy (c.m.) MeV	d_o, fm
$^6He + ^{208}Pb$	55	1.65±0.05
$^6Li + ^{208}Pb$	51	1.65±0.03
$^9Li + ^{208}Pb$	82	2.1 ± 0.05

Note, that d_o parameters appeared to be practically equal to ^6Li and ^6He scattering. As it is seen from fig. 6 and table 2, the determined values of d_o for ^9Li are significantly higher than for ^6Li. For value σ_{el}/σ_R, equal to 0.25 one can obtain the value of effective interaction radius. In table 3 the values of r_c parameter for ^6Li, ^6He and ^9Li obtained from experiment characterizing these radii are given. For comparison, the values r_c obtained earlier for elastic scattering of ^6He and ^9Li and Ag nuclei |19| are also shown there. The comparison of these values for ^9Li, obtained

Table 3. Comparison of r_c parameter at scattering on A g and ^{208}Pb

Nucleus	Energy (c.m.) MeV	r_c on Ag, fm	r_c on Pb, fm
^6He	55	1.49±0.04	1.5±0.05
^9Li	82	1.57±0.05	1.87±0.05
^8He	43	1.57±0.05	–
^7Li		–	1.43±0.03
^6Li		–	1.49±0.03

from elastic scattering on Ag and Pb shows that such r_c parameter increases at interaction with ^{208}Pb cannot be related with nuclear absorption. Such increase of effective radius on ^{208}Pb can be caused by other factors such as the Coulomb dissociation of ^9Li in the field of ^{208}Pb nucleus or dynamical polarizability of ^9Li nucleus in the field of ^{208}Pb nucleus. It is possible that in the given scattering processes the Coulonb rainbow scattering gives a predominant contribution that leads to strong deviation from the Rutherford scattering |21|. It is of interest to analyze these factors

on the ground of different model concepts.

In connection with this the experimental elastic scattering cross sections of ^9Li on ^{208}Pb, showing anomalies were analyzed in the framework of the optical model (OM). The calculations were performed both with a phenomenological optical potential and a semimicroscopical potential of a double-folding model. Such data analysis on ^9Li will be reported at this School. Evidently, that the works connected with secondary beams on studying the properties of exotic nuclei in spite of their difficulties can provide a number of new results for further development of model approximations.

Our immediate plans for the investigation of exotic nuclei properties and of reactions on secondary beams formed of such exotic nuclei are connected with the improvement of heavy ion accelerators of JINR, construction of new separating channel of secondary particles (COMBAS) on-line with a 4π- detector (FOBOS).

It is expected that in 1992-1993 intensive extracted heavy ion beams ($\sim 10^{13}$ pps) with $A \leq 40$ and energies up to 100 MeV/nucleon will become available for the researchers. This will provide increased production of secondary particles. The separating channel COMBAS will allow to purify secondary particle beams from the primary heavy ion beam in order to transport and focus the secondary beam on the target of the detector array (FOBOS). |22|

FOBOS provides wide possibilities for studying both light and heavy products of nuclear reactions since it includes 3 subsystems: an array of 190 phoswich telescopes, 30 combinations of position sensitive avalanche counters with axial ionization chambers and a special forward wall |23|.

Wider prospects of researches on secondary beams at JINR will be opened at the construction of the heavy ion storage Ring Complex K4-K10 |24| which will include the existing heavy ion accelerators of the Laboratory of Nuclear Reactions, the shaping ring K-4 with electron cooling of particles and the synchrotron accelerating ring K-10.

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Исследование β-задержанной нейтронной эмиссии и упругого рассеяния нейтроноизбыточных изотопов гелия и лития

Описан один из методов получения легчайших нейтронообогащенных ядер в качестве вторичных пучков, которые сформированы из продуктов реакций с тяжелыми ионами с энергией 20 МэВ/нуклон. Сооружена установка, позволяющая измерять периоды β-распада легчайших ядер, вероятности β-n-задержанной эмиссии и распределения по множественности испускаемых при этом нейтронов. Эффективности регистрации β-частиц составляют 0,95, а нейтронов - 0,315. Измерены периоды полураспада и вероятности β-n эмиссии изотопов ^{8}He, ^{9}Li, ^{11}Li, ^{12}Be и ^{13}B. С помощью трековых детекторов типа CR-39 изучено упругое рассеяние ядер ^{6}He и ^{9}Li на ядрах ^{208}Pb. Анализ данных по сечениям упругого рассеяния ^{9}Li показывает, что ^{9}Li при периферических взаимодействиях имеют довольно большую прозрачность. Предполагается в процессе рассеяния сильная динамическая поляризация ^{9}Li в поле тяжелого ядра ^{208}Pb.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

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Investigation of β-Delayed Neutron Emission and Elastic Scattering of Neutron - Rich Isotopes of He and Li

One of the methods to obtain the lightest neutron-rich nuclei as secondary beams is described. Secondary beams are formed from a nuclear reaction due to heavy ions with the energy of ~20 MeV/nucleon. A set-up is constructed which allows to measure half-lives of β-decay, probabilities of β-delayed neutron emission and neutron multiplicities. The efficiencies for detection of β-particles are 0.95, of single neutron - 0.315. The half-lives probabilities of β-delayed neutron emission and neutron multiplicities for decay of ^{8}He, ^{9}Li, ^{11}Li, ^{12}Be and ^{13}B were measured. The elastic scattering of ^{6}He and ^{9}Li was also studied. The data analysis of the measured elastic cross-section shows, that the peripheral ^{9}Li interaction region has a rather high transparency. Strong dynamical polarization of the ^{9}Li nucleus in the field of the heavy nucleus of ^{208}Pb in the process of scattering is proposed.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

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