сообщения
объединенного
института
ядерных
исследований
дубна

E7-93-74

Artukh, A.G.

STUDY OF PROPERTIES OF Ne - Al NEUTRON RICH ISOTOPES AT AND NEAR $N = 20$ MAGIC SHELL USING ELASTIC SCATTERING IN INVERSE KINEMATICS*

---

*Proposal and Technical Proposal for the experiments on the intermediate energy heavy ions

1993

A.G.Artukh, S.N.Ershov, F.A.Gareev, G.F.Gridnev, M.Grushecki, S.Kliczewski, M.Madeja, S.Yu.Shmakov, J.Szmider, Yu.G.Teterev, V.V.Uzhinski
Joint Institute for Nuclear Research, Dubna, 101000 Moscow, Russia

K.Holy, P.Povinec, B.Sitar
Comenius University, Faculty of Mathematics and Physics, 8421 15 Bratislava, Slovakia

Yu.M.Sereda, I.N.Vishnevski
Institute for Nuclear Research, Kiev, Ukraine

1 Physical problem

Recent experimental study of the lightest and light neutron rich nuclei have brought a lot of interesting information on the properties of nuclei with abnormal ratio N/Z and on the many-body problem of quasi-neutron matter [1].

First of all, systematic experimental study of the neutron drip- line position in $C-, N-, O-$ isotopes have shown that $N = 16$ neutron number is a new shell closure, while the shell closure at $N = 20$ tends seems to disappear for Ne and heavier neutron rich nuclei on the contrary region of stable nuclei.

Secondly, the anomalies in the behavior of the binding energy (two-neutron separation S_{2n}) for Na-isotopes [2]-[4] with a large neutron "overdose" near shell magic $N = 20$ (Fig.1a); the abnormal ground state spin at ^{31}Na and the very low excitation energy of the 2^+ state in ^{32}Mg suggest the existence of a large ground-state deformation that contradict the expectations of a standard shell model [5, 6].

The evidence on "losses magic" of $N = 20$ shell closure and occurrence of new neutron magic numbers have been interpreted [7] as "the collapse of the shell model" and force to revise its basis radically.

Two basic theoretical approaches have been taken [6, 8]-[11]. The first is essentially the Strutinsky shell correction method and the second incorporates an explicit dependence of nuclei properties on proton and neutron number through a proton - neutron force. The latter approach predicts shape coexistence (or shape isomerism) which will be found near closed shells when the other type of nucleon is near mid shell. Subshell also plays a role . They can suppress shape coexistence if they occur at or near mid shell for a closed shell for the other type of nucleon and they can give rise to shape coexistence by playing the role of major closed shells.

Results of theoretical fitting [9] of the experimental masses for several Na heavy isotopes at and near "magic shell" $N = 20$ are shown in Fig.1b. From this Figure it is seen that the energy potential with neutron number evolves from spherical to strong deformed configurations, while in the transitional cases of shape coexistence both compact spherical and prolate deformed configurations are occurring.

The observed overbinding energy in comparison with the shell model predictions for the neutron rich nuclei and the existence of shape isomers would have dramatic consequences both for theoretical models [6, 7, 11] and our understanding of nuclear stability limit. Really the boundary of nuclear stability can be considerably shifted to super- neutron rich isotopes and the existence of the shape isomers for the loosely-bound neutron rich nuclei can lead to appearance of the quasi-stability islands of quasi-neutron nuclei beyond the neutron drip-line position.

The factors controlling shape coexistence are rather subtle and not always simple. Furthermore, it is known that the extrapolation of the properties from the stable nuclei to exotic neutron-rich nuclei does not describe static deformation phenomena near neutron shell closure.

Thus, it is necessary to carry out systematic experimental study for the neutron number dependence of the nuclear deformation as it approaches to stability limit.

The important information about shapes of the exotic nuclei can be obtained from the scattering experiments with the secondary radioactive beams. It is known that elastic cross sections at low and intermediate projectile energies show the Fraunhofer diffractive picture at the small angle region and for greater angles it displays a nuclear "rainbow-like" phenomena. The small angle region corresponds to the far peripheral interactions, i.e. one can say that the cross section σ_{el} is determined by the "tail" of the single particle distribution at the large distances. Therefore one can obtain from these data an important information about the root-mean-square radius of the single particle distributions and information about optical potential details at very low densities of the nuclear matter. Moreover the period of the Fraunhofer diffractive oscillations is determined by the radius of strong absorption as $\delta\theta = \pi/kR_{abs}$, where k is a wave number. One more details about the nuclear structure we expect to obtain from measuring the cross section $\sigma_{el}(\theta)$ as the angle θ increases. Therefore it is necessary to start the investigations just from the elastic scattering as it was done by GANIL [12] and RIKEN [13]

We propose to study the evolution of the properties of the large group heavy isotopes for light elements from Ne to Al near and at the $N = 20$ neutron shell versus increase of neutron excess in the elastic scattering of this nuclides on the protons. For this group isotopes experimentalists [14, 15, 16] have already measured masses with sufficient accuracy and there are evidences on possible onset of a new region of deformation at the $N = 20$ neutron shell closure for ^{31}Na and ^{32}Mg isotopes.

It should be noticed that the updated intensities of secondary beams of exotic nuclei are rather low because these experiments demand high effectiveness and high informativeness of the detecting complex.

2 4π-geometry tracking detector multiplicity used in regime detector-target-detector

The study of rare decays (processes) of the exotic nuclei with ultrasmall yields make use of the detecting complex which would provide the measurements of a full multiparticle kinematics and simultaneous carry out unambiguous identification of all type particles.

The time projection chamber TPC as an electronic tracking detector allows three-dimensional reconstruction of multitrack events with a high spatial resolution and identification of charged particles by ionization sampling [17, 18]. Furthermore,the large sensitive gas volume of the TPC and its property to visualize all the tracks of multi- particle process permits to use effectively the detector TPC itself in the mode detector-gas target-detector. Thus, we can reach the 4π-geometry for simultaneous registrations both the unstable projectile and the nuclei- recoil of the working gas. Principle of operating of a TPC assembly is shown in the Fig. 2a),2b) , detailed description was presented in report [19].

The TPC is a perspective detector for full-scale study of the binary processes of elastic and inelastic scattering unstable projectiles on the simplest nuclei of the gas-filled detector in the inverse geometry (mass projectile larger than mass gas target). In the inverse kinematics by use of TPC one can measure:

- the tracks of both partners simultaneously;
- the scattering angles of both nuclei (angular correlations);
- to determine the energies of both partners (in the ranges and stopping-power or on magnetic rigidity by installation TPC in magnetic field);
- to measure the trajectory entry of projectile to target (for precise determination of entry angle and point interaction projectile also);
- to study the excitation function (cross-sections versus energy projectile by slowing its in stopping processes);
- to separate inelastic and elastic processes with sufficient accuracy.

The advantages of the method are evident in the cases when it is necessary to measure the elastic scattering near zero angle or its excitation function (potential and resonance) at 180° c.m. (back semisphere) by registration of recoil-particle.

Furthermore, the elastic scattering on the lightest nuclei (on the protons in mixture CH_4 or helium-filled TPC) is especially convenient for theoretical analysis because it simplifies a problem of interpretation of the results obtained by excluding the structure of the simplest recoil-nuclei.

The existing TPC at JINR Dubna has sensitive volume $0.35 \times 0.8 \times 1.6 m^3$. Stainless steel gas box has dimensions: $0.5 \times 1.2 \times 2.0 m^3$, it is designed for atmospheric pressure. The TPC has 80 layers of 20 mm thick for ionization sampling. Vertical coordinate (Z) is measured by electron drift time with 0.2 - 0.5 (mm) accuracy. horizontal (Y) by delay lines with 1-2 mm accuracy. The double - track resolution is 8 mm and 30 mm in Z and Y coordinates, respectively. The TPC is working well in magnetic field up to 1.5 Tesla and in the flux up to 5×10^5 minimally ionizing particles per second. When heavily ionizing nuclei are registered gain have to be lowered, so the counting rate can remain the same. The chamber can be triggered, which sufficiently increases its counting rate capability. The electron sampling time is 7-10 microseconds.

The electronics of the existing TPC: 80 anode channels including preamp., adjustable amp. and FADC - 6 bit, 64 ns sampling period, 16 μs full sampling time, 256 samples. In non-linear mode the FADC dynamic range can be extended to 8.5 bit, but with deterioration of the resolution. 40 channels of cathode electronics (on both sides of a delay line) consist of: preamp., adjustable amp. and 14 bit MHTDC. The electronics (FADC) should be tested yet.

At present optimization of TPC parameters is carried out on the ion beam for Z region up to 25. The existing TPC for proposed experiment on protons in inverse kinematic can not be used because, firstly, configuration of TPC from a single proportional plate counter does not permit to register effectively recoil-protons near 90°. lab. system and, secondly, quality of our electronics is not sufficient.

For the COMBAS separator Dubna prepare a new TPC. Its parameters should fit proposed experiments at ion beams but it should be a universal vertex tracking detector. It should have pressurized vessel (0.1-5 atm). TPC structure for operation in the regime detector-target-detector is shown in the Fig. 2c). Its sensitive volume will be $30 \times 100 \times 150 cm^3$. Gas box has external dimensions : $40 \times 120 \times 200 cm^3$. The TPC can operate in the magnetic field $\vec{B} \parallel \vec{E}$ $(B \leq 2T,\ E \leq 500V/cm)$. The electrons are drifted to the proportional chambers in the bottom of the TPC. The TPC is divided into 3 volume : $N1$. target and detecting projectile volume simultaneously; $N2, N3$ - recoil particle volume. All the volumes are inside the common drift volume, they are defined only by the structure of a proportional chamber. The structure of the $N2$ and $N3$ volumes are similar. Each sampling layer in the TPC is 2 cm (may be 1 cm) wide. The length of the anodes is: 10 cm in the area $N1$, 150 cm in the area $N2, N3$.

Two systems of the second (horizontal) coordinate read-out can be used: a) delay line read-out, b) cathode pad read-out. The distances between the delay lines (DL or cathode pad rows (CPR) are 10 cm (may be 5 cm) in any area, e.g. there will be 17 delay lines (or CPR), of 10 cm long in the target area, 10 DL (or CPR) 150 cm long in the recoil particle area for $N2$ and $N3$, respectively. The Y coordinate of the projectile is measured in 17 points, Z coordinate and dE/dX in 32 points. The X coordinate of a recoil particle track is measured in 5 points, Z coordinate and dE/dx in 20 points for $N2$ and $N3$ areas, respectively. All these should provide sufficient precision of the angle momentum and dE/dX measurements.

Electronics for the new TPC should contain $75 + 20 + 20 = 115$ anode channels (preamp., + amp. + FADC). The number of cathode electronics channels (preamp. + amp. + FADC) depends on the read-out system, which will be adopted. For the delay line read-out it will be $(17 + 10 + 10) \times 2 = 74$ channels (or 148 channels for the distances between DL is 5 cm). The spatial resolution (rms) for 10 cm DL are 0.1 mm and for 150 cm DL - 1-2 mm. The cathode pad read-out (the width of a cathode pad is 5 mm) : $20 \times 17 + 200 \times 10 + 200 \times 10 = 4340$ channels. The spatial resolution $\sigma(y)$ (rms) will be at any point 0.1-0.2 mm. The total number of the channels is 189 for DL read-out and 4455 channels for the cathode pad read-out.

The proposed TPC should be an universal vertex tracking detector for the angle distribution and momenta measurements with an identification capability. The final decision about the chamber dimensions and parameters should be made after testing of the studied reactions at Lab. of Nucl. Reactions.

The 189 information channels (e.g. for DL) of the TPC force to use multichannel and very fast (for tracks resolution) electronics modules (for example STRUCK and LECROY corporations). In Fig.2c) the possible structure of the electronic module is shown.

3 Kinematic analysis of elastic scattering Na isotopes and optimal choose of experimental condition

The optimal reaction for production of the proposed heavy isotopes group of $Ne-Al$ light elements seems to be ^{40}Ar fragmentation with energy region $50 - 100 MeV/A$.

In Fig. 3a),b) and 4a),b) angular distribution (cm and lab. system) of two isotopes $^{23,32}Na$ for two energies (for comparison) are shown . As seen, the projectile angular distribution is focusing in narrow forward cone ($\theta^{Na}_{lab} < 2°$). In this situation the registration of projectiles only demands to provide very high precision of angle measurements, while associated recoil-protons (Fig. 4b) have a wide angular distribution (up to $\Theta_{lab} \simeq 90°$), which is very convenient for registration.

Taking into account the very low expected intensities of ^{32}Na radioactive beam one can consider that range of angular distribution measurements in this experiment can reach the second and third minimum position only. For ^{32}Na projectile with 50 MeV/A energy this corresponds to the angular region $\Theta^{Na}_{lab} \simeq 0° - 2°$, while for recoil-protons an angular region is $\Theta^{p}_{lab} \simeq 55° - 90°$, respectively.

Therefore, the maximum angular sensitivity of TPC for both partners must be concentrated in this angular regions. Choosing of the TPC configuration (Fig. 2c) was determined by these requirements.

In Fig. 5b an energy distribution (lab. syst.) of two $^{23,32}Na$ isotopes at three energies of the projectile versus their scattering angle are shown. In Fig. 5c the same energy-angle $[E_p, \Theta_p]$ correlations but for recoil-protons are presented. The angle-angle $[\Theta^{Na}_{lab}, \Theta^{p}_{lab}]$ correlation for $^{23,32}Na$ projectiles and their recoil-proton partners are presented in Fig. 5a. In Fig. 5a a rectangle angular region $[\Theta^{Na}_{lab}, \Theta^{p}_{lab}]$ of the projectiles and recoil-protons optimal for TPC registration (determined from conditions of low intensities of unstable projectile) are shown. This $[\Theta^{Na}_{lab}, \Theta^{p}_{lab}]$ region contains more than 90 % of the elastically scattered particles and it depends weakly on the projectile energy. For detailed analysis outlined rectangle $[\Theta^{Na}_{lab}, \Theta^{p}_{lab}]$ angle-angle correlation is shown in Fig. 6a) and b) in enlarged scale for ^{23}Na and ^{32}Na isotopes with the 50 MeV/A energy. In the same Fig. 6a) and b) we show the dependence of $[\Theta^{Na}_{lab}, \Theta^{P}_{lab}]$ angle-angle correlation on inelasticity of the scattering process.

From Fig. 6a and 6b an extremely high sensitivity of an angle recoil-protons Θ^{p}_{lab} is demonstrated even at such small energy variations as 1 or 2 MeV in comparison with 1.6 GeV total initial energy of ^{32}Na projectile and 1.1 GeV initial energy of

^{23}Na projectile. For separation of an inelastic processes from elastic ones with accuracy $\Delta E = E^* = 1MeV$ it is necessary to realize angular resolution better than $0.5°$ for recoil-protons and better than $0.1°$ for projectile in discussed angular regions. The spatial resolution of the TPC chamber with good electronics in proposed configuration (Fig. 2c) is sufficient to reach necessary angular resolution.

Concerning energy resolutions and possibility of separation inelastic-elastic processes we present in Fig. 7a) and b) energy-angle $[E_p, \Theta_p]$ correlation for ^{23}Na and ^{32}Na isotopes. From Figs. 7a) and b) it is seen that separating of inelastic-elastic processes with accuracy 1 MeV requires to rich energy resolution for recoil-protons better than 2%. This energy resolution is reached for the cases of total stopping for recoil-protons in sensitive volume of the TPC. To achieve the better separation of inelastic-elastic processes on the energy, the TPC should be installed in magnetic field.

4 Estimation of effect

Let us estimate the necessary integral beam and exposure time for elastic scattering of the radioactive nuclei ^{32}Na with 50 MeV/A, for example, the energy. In Table 1 calculated cross sections σ_{reac} and elastic cross section in the angular bins corresponding to the 2nd and 3d maxima and their sum, respectively, are presented.

E(MeV)	15	30	50	$\sigma(mb)$
^{23}Na	883	711	472	σ_{reac}
	1050	980	730	$\Delta\sigma_{el}(2nd)$
	1170	1080	790	$\Delta\sigma_{el}(2nd+3d)$
^{32}Na	1326	1185	688	σ_{reac}
	1100	1100	976	$\Delta\sigma_{el}(2nd)$
	1180	1140	1120	$\Delta\sigma_{el}(2nd+3d)$

In the 4π geometry efficiency of detecting by TPC the number of ^{32}Na elastic interactions with protons (CH_4 gas-filled TPC) under one atmosphere pressure is equal to $n_p\Delta\sigma(2nd) \approx 9.8 \cdot 10^{-5}\ cm^{-1}$, where proton concentration $n_p \approx 10^{20}\ cm^{-3}$ and $\Delta\sigma(2nd) \approx 9.8 \cdot 10^{-25}\ cm^{-2}$ (see the table). The n_p calculations take into account protons in CH_4 molecule $n_p \approx N_A \cdot 4/22400 \approx 10^{20}\ cm^{-3}$. The sensitive length L of TPC is 150 cm, therefore $n_p\Delta\sigma(2nd) \cdot L \approx 1.5 \cdot 10^{-2}$. To achieve 1% accuracy of the measurement, of about 10^4 events are required. In this case we have to use $10^4/1.5 \cdot 10^{-2} \approx 7 \cdot 10^5$ total integral of ^{32}Na particles. If we have ^{32}Na intensity about $10^2\ p/s$ then the exposure time of the experiment $\Delta t \approx 7 \cdot 10^5/10^2 = 7 \cdot 10^3 s \approx 2$ hours. This exposition is sufficient for measurement in the region of the first and second diffraction maxima.

There is an opportunity to increase the efficiency of the experiment. The number of working protons can be increased considerably by a series of mylar insulating foils (targets) with thickness $\sim 50\mu$ on the beam trace in the sensitive TPC volume. These additional mylar targets should be installed inclined in two axis in order to

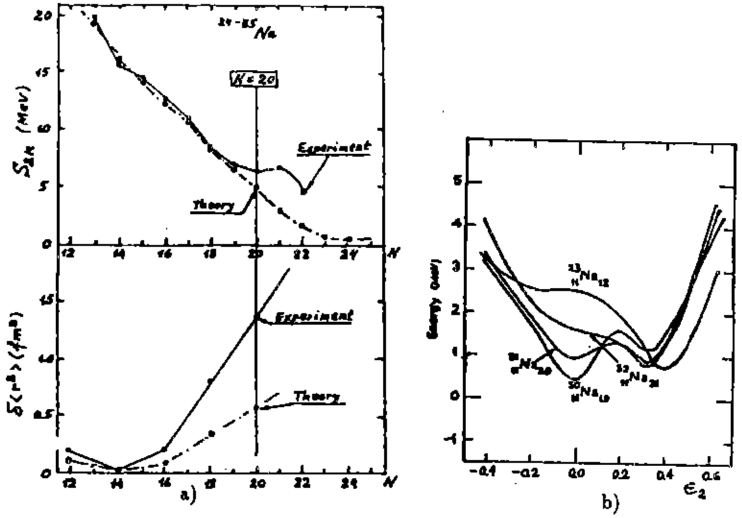
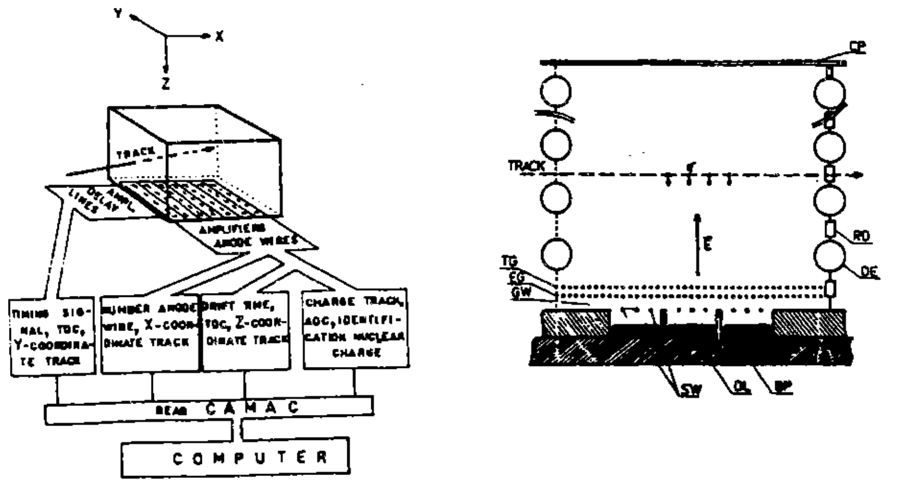


Fig.1 a). Two neutron energy separation (upper) and the root-mean-square radius versus neutron number of Na isotopes.
b). The behavior of potential energy for Na isotopes versus quadrupole deformation parameter.



a) b)

Fig.2 a),b). The principle of the TPC assembly operating. DL – delay line, SW – signal (anode) wives, GW(EG) – field-forming (earthed) wives, TG – trigger grid, RD – divider, CP – cathode, BP – the main plate.

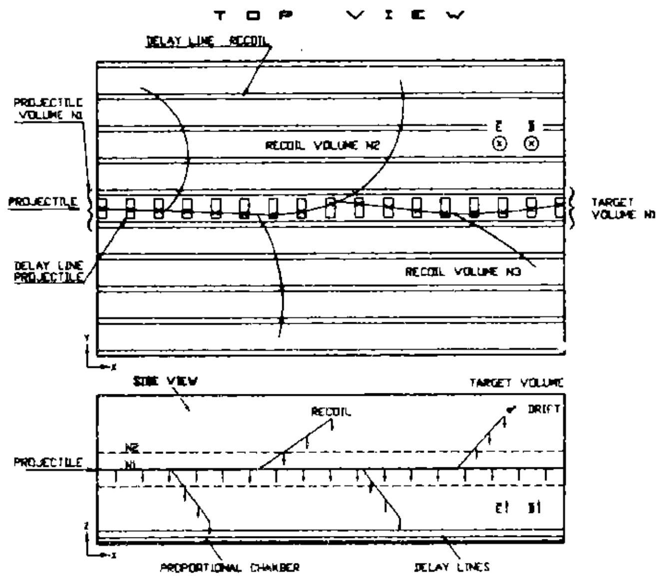


Fig.2 c). The TPC structure for detector-target-detector operating mode.

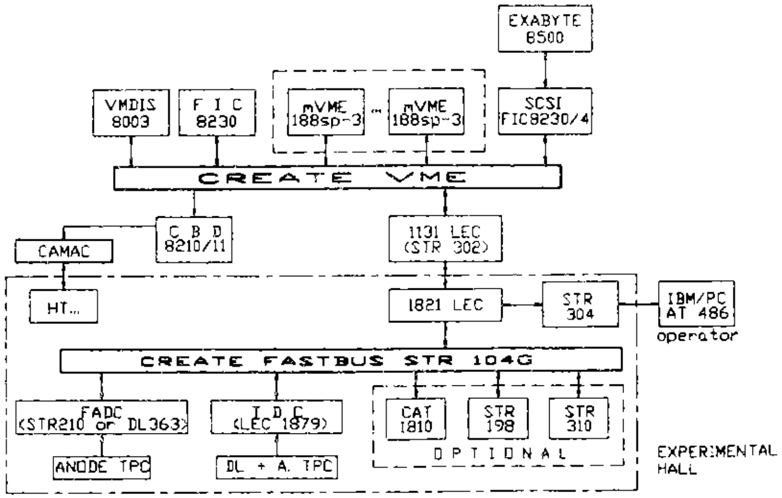


Fig.2 d). The structure of the TPC electronic module.

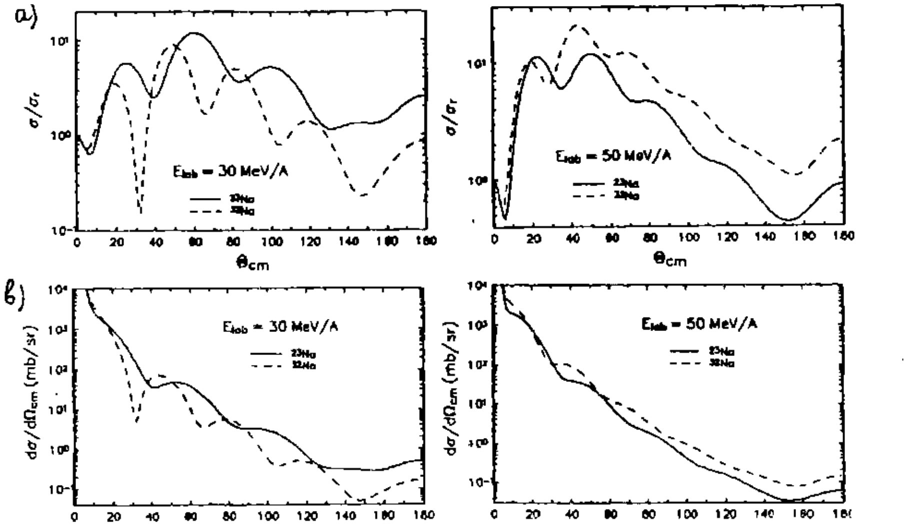


Fig.3 a),b). The elastic to Rutherford cross section ratio as a function of the center mass scattering angle at 30 MeV/A and 50 MeV/A energies (lab. system) for $^{23,32}Na$ isotopes respectively and the differential elastic cross section (CM system) of these isotopes.

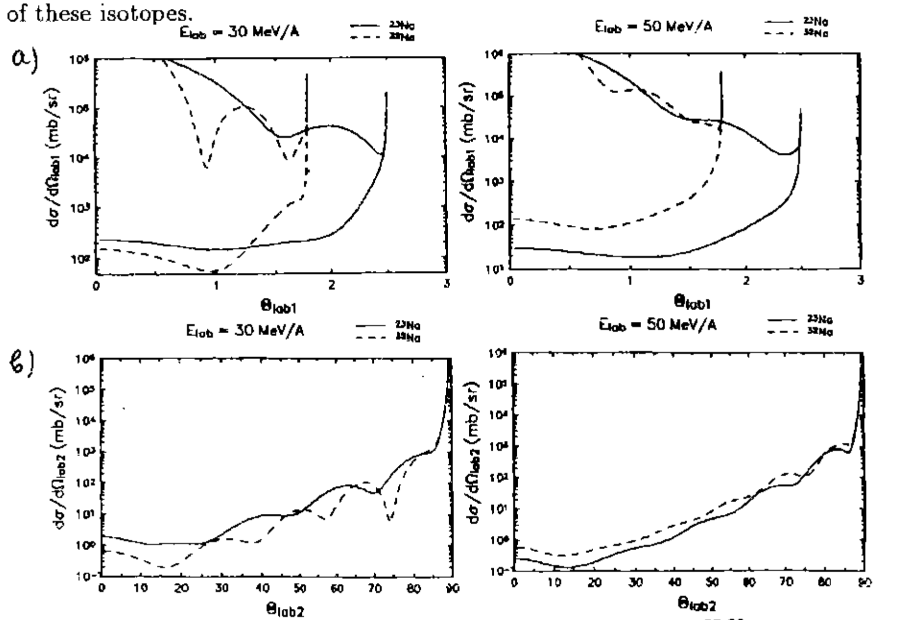


Fig.4 a). The differential elastic cross section (lab system) of $^{23,32}Na$ projectiles versus its lab. scattering angle at 30 MeV/A and 50 MeV/A energies.

b). The differential elastic cross section (lab system) of recoil protons versus its lab. scattering angle.

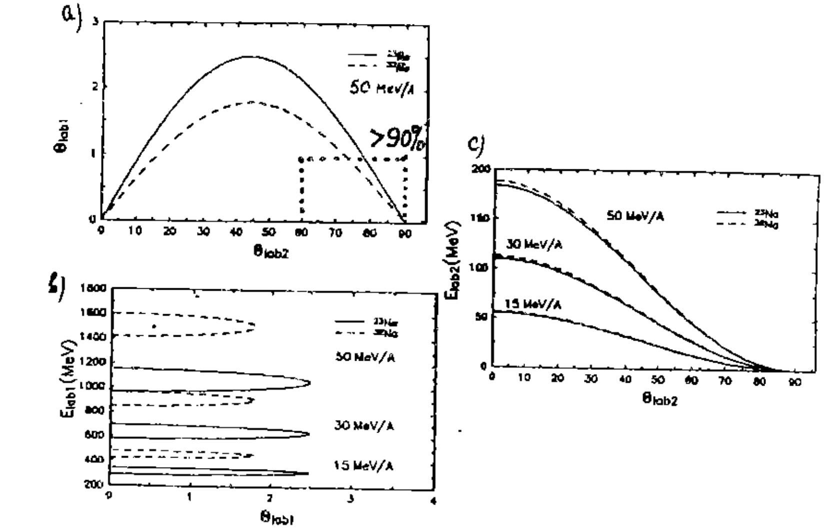


Fig.5 a). Angle-angle $[\Theta_{lab1}, \Theta_{lab2}]$ correlations for $^{23,32}Na$ isotopes.
b). Energy-angle $[E_{lab1}, \Theta_{lab2}]$ correlations for $^{23,32}Na$ isotopes in the lab. system.
c). Energy-angle $[E_{lab1}, \Theta_{lab2}]$ correlations for recoil protons in the lab. system.

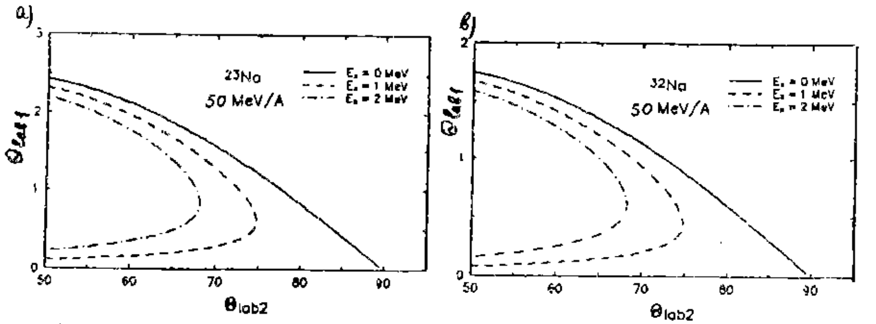


Fig.6 a) and b). Enlarged scale angle-angle $[\Theta_{lab1}, \Theta_{lab2}]$ correlations for $^{23,32}Na$ isotopes.

exclude losses of low energy recoil protons in the $60 - 90°$ angular region. The additional targets allow to increase summary density of protons to factor of tens and, therefore, to decrease correspondingly the exposure time. This procedure can, in principle, achieve the higher diffraction maxima region.

5 Using of the TPC for drip-line protons study

Possibility of three-dimensional reconstruction of multitrack events with a high spatial resolution and simultaneous identification of their charges by TPC can be effectively used for systematic studying of rare decays for proton-rich nuclei near and

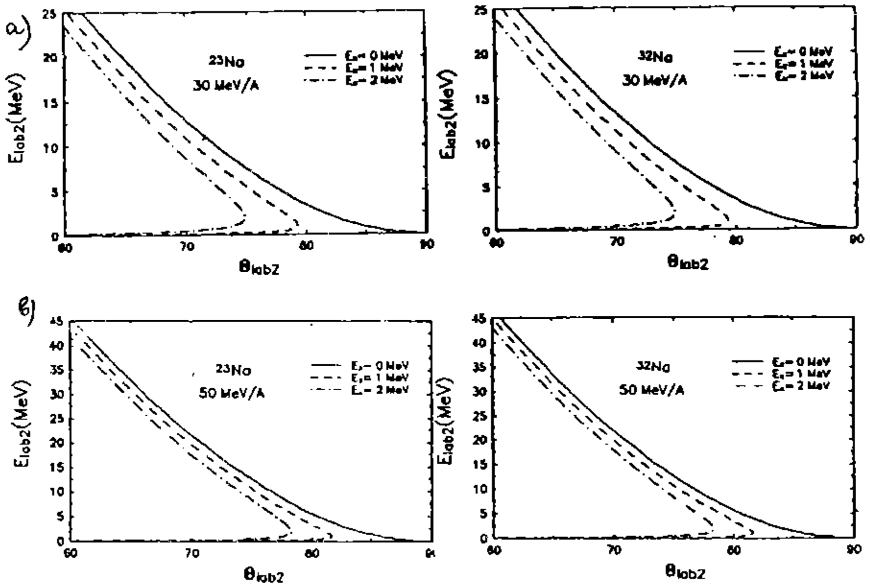


Fig.7 a),b). Energy-angle $[E_{lab1}, \Theta_{lab2}]$ correlations for recoil protons in the lab. system at large angles.

beyond drip-line, for example, for the investigation of the direct or beta-delayed proton and heavier charge particles emission (cluster radioactivity).

It is known as approaching to the ground-state proton drip-line, β- delayed particle emission takes place. In the last process, the particle emission is resulted from excited states of daughter nuclei populated in the decay. Experimental investigations of the proton radioactivity show that branches ratio β_{2p}/β_{1p} strongly increases at approaching to proton drip-line and energy decays $Q_{2p} > Q_{1p}$ can occur. In the case of $Q_{2p} > Q_{1p}$ and $Q_{2p} < V_{2p}$ (V_{2p} is the Coulomb barrier of $2p$-emission), the direct 2p emission from the unbound nuclei on and beyond proton drip-line is expected. The existence of the Coulomb barrier V_{2p} in the weakly unbounded nuclei ($Q_{2p} \leq -1MeV$) with $Q_{2p} < V_{2p}$ leads to considerable delay of their Coulomb subbarrier-decays (τ-delay $\approx 0.1 - 1.0ms$).

Investigations of the direct 2p-emission from the ground state exotic nuclei are possible by the TPC detector. It is predicted that candidates at the direct $2p$-emission are $2p$-unbound nuclei $^{34}Ti, ^{42}Cr, ^{45}Fe$ and ^{48}Ni.

6 Acknowledgements

This proposal is a parallel version of the proposal for the relativistic energy heavy ions which has been prepared in collaboration with the group of Pr. G.Müenzenberg (GSI, Darmstadt). The authors are indebted to Yu.Ts.Oganessian, Yu.E.Penionzhkevich, V.V.Volkov, V.L.Mikheev and M.I.Tarantin for grateful discussions.

References

[1] 2dth Int. Conf. on Rad. Nucl. Beams, August 19-21, 1991, Belgium.

[2] C.Detraz et al., Phys. Rev. C19, 164 (1979) J.J.Vieira et al.. Phys. Rev. Lett. 57, 3253 (1986)

[3] C.Detraz et al., Nucl. Phys.A 394, 378 (1983)

[4] D.Guillemaud-Mueller et al., Nucl. Phys.A 426 (1984) 37

[5] X.Campi et al., Nucl. Phys.A 251 (1975) 193

[6] Yu.S.Lyutostansky et al., Proc. 5th Inf.Conf. on Nuclei Far from Stability, Ontario-Canada, 1987, p.727

[7] W.Chung and B.H.Wildenthal, Phys. Rev. C22 (1980) 2260

[8] K.Heyde et al., Phys. Repts. 102, 291 (1983) K.Heyde, Proc. 5th Int. Conf. on Nuclei Far from Stability, Ontario- Canada, 1987 and Nucl. Phys.A 466 (1987) 1891

[9] R.Bengtsson et al., LA- UR- 83- 1834, 1983 P.Mollerr and J.R.Nix., At.Data Nucl. Data Tables 21, 165 (1981)

[10] J.L.Wood, in "Proc. Int. Symposium on In-Beam Nuclear Spectroscopy" Debrecen, Hungary, may 14-18 (1984)

[11] R.J.Lombard, in "Proc. Workshop on Nuclear Structure of Light Nuclei far from Stability", Obernai, France, novemb. 27-29, 1989

[12] W.Mittig et al., Phys. Rev Lett. 59 (1987) 1889

[13] I.Tanihata, preprint RIKEN- AF- NP- 59

[14] A.S.Dem'yanova et al. *Phys. Scripta* **32** (1990) 89

[15] N.A.Orr et al., preprint GANIL P 9102, 1991

[16] X.G.Zhou et al., preprint Los Alamos National Laboratory, 1991

[17] F.Sauli, Z.Phys. C38, 339 (1988)

[18] B.E.Bonner et al., Preprint BNL-42189, 1988

[19] A.G.Artukh et al.,2th Int. Conf. on Rad. Nuclei Beams, August 19-21, 1991, p.27, Belgium

Received by Publishing Department

on March 11, 1993.