ISSN 1344-3879
RIKEN-AF-NP-372
RIKKYO-RUP-00-06

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with intermediate-energy radioactive ion beams**

T. Motobayashi

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August 2000

The Institute of Physical and Chemical Research (RIKEN)
2-1 Hirosawa, Wako, Saitama 351-0198, Japan
TEL: (048)462-1111 FAX: (048)462-4642
e-mail: username@rikvax.riken.go.jp

Talk given at the Nuclear Structure 2000
(NS2000) Symposium held at Michigan State University,
August 15-19, 2000

Nuclear astrophysics experiments with intermediate-energy radioactive ion beams

Tohru Motobayashi

Department of Physics, Rikkyo University,
3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan

Experimental studies of nuclear astrophysics using intermediate-energy radioactive ion beams at RIKEN are presented. To overcome the low intensity and low emittance of the beams, we employed Coulomb dissociation and Coulomb excitation with reversed kinematics where the excitation energy is determined by measuring invariant masses or de-excitation γ -ray energies. Various (p, γ) reactions in the pp chain, the hot- and regular-CNO cycles and the hot pp mode were investigated indirectly.

1. EXPLOSIVE BURNING AND UNSTABLE NUCLEI

Stellar nuclear-burning may involve short-lived nuclei if capture reactions on certain nuclei become faster than their weak decays. This occurs predominantly in “explosive” conditions where the temperature and density are high. Even in non-explosive situations as in the hydrogen burning in the sun, unstable nuclei are sometimes important as will be discussed. These capture processes are, however, difficult to study in laboratory experiments, especially when the nucleus is short-lived and difficult to be used as a target. An alternate possibility is to use radioactive ion (RI) beams. Direct measurements of the reaction cross sections can be performed by using a low-energy beam of the nucleus of interest. Another possibility is to determine the cross sections indirectly by a nuclear reaction such as, resonant scattering, transfer reactions [1], or Coulomb dissociation.

We have developed indirect methods using intermediate-energy beams of unstable nuclei. Compared with ordinary beams of stable particles, the quality of RI beams is generally very poor:

- (i) The beam intensity is quite low. For example, intensities of intermediate-energy beams of ${}^8\text{B}$, ${}^{14}\text{O}$ and ${}^{32}\text{Mg}$ were 10^4 , 10^4 , 10^2 s^{-1} , respectively [2]. Even more intense ${}^{13}\text{N}$ beams of 10^8 s^{-1} at Louvain-la-Neuve [3] are still much weaker than, for example, a proton beam of 10^{12} s^{-1} which corresponds to 0.1 μA .
- (ii) The emittance is large especially for intermediate-energy RI beams produced by fragmentation. Typical beams at RIKEN are of a few % energy spread, 1-2° angular spread and a beamspot size of 20-30 mm diameter.

Therefore, to extract useful information from experiments, we have to develop new efficient tools: reactions with large cross sections and experimental setups with high efficiency. Efforts to overcome the poor quality of the beams should also be made to resolve the final states of the reaction.

2. COULOMB DISSOCIATION

2.1. Characteristics of the Coulomb dissociation method

The Coulomb dissociation method has been extensively applied to the investigation of astrophysical problems at RIKEN. To study the radiative capture reaction $A(x,\gamma)B$, the residual nucleus B bombards a high- Z target and is Coulomb excited to an unbound state that decays to the channel $A+x$. Since the process is regarded as absorption of a virtual photon, *i.e.* $B(\gamma,x)A$, the radiative capture (the inverse of the photoabsorption) cross section can be extracted from the dissociation yield. This idea was first proposed by Baur, Bertulani and Rebel [4] based on the semi-classical virtual photon theory. Topical reviews were given by Baur and Rebel [5]. In addition to the advantage of the possibility to use thick targets, the Coulomb dissociation method enhances the original capture cross section by a large factor due to the large virtual-photon number and the phase space factor. As an example, Table 1 compares two measurements studying the hot-CNO cycle reaction $^{13}\text{N}(p,\gamma)^{14}\text{O}$. The table compares parameters for the Coulomb dissociation measurement [6] and the inverse kinematics direct reaction where a low-energy ^{13}N beam bombards a hydrogen target [3]. In spite of the much higher intensity of the direct measurement, the experimental yield is higher for the Coulomb dissociation measurements, indicating the larger experimental efficiency of the latter.

Table 1

Comparison of the Coulomb dissociation (Cd) and direct capture (dc) measurements for the $^{13}\text{N}(p,\gamma)^{14}\text{O}$ reaction.

	Coulomb dissociation ^a	direct capture ^b	Ratio: Cd/dc
Projectile	^{14}O	^{13}N	
Beam energy	87.5 AMeV	0.6 AMeV	
Beam intensity	$3 \times 10^4 \text{ s}^{-1}$	$3 \times 10^8 \text{ s}^{-1}$	10^{-4}
Target material	^{208}Pb	$(\text{CH}_2)_n$	
Target thickness	350 mg/cm ²	180 $\mu\text{g}/\text{cm}^2$	65
Cross-section	10 mb	100 μb	10^2
Efficiency	0.5	2×10^{-3}	350
Data taking	36 h	30h	1.2
Total counts	1.5×10^4	85	180

^a $^{208}\text{Pb}(^{14}\text{O}, ^{13}\text{N} p)^{208}\text{Pb}$ at RIKEN [6]

^b $^1\text{H}(^{13}\text{N}, \gamma)^{14}\text{O}$ at Louvain la Neuve [3]

In Coulomb dissociation experiments with intermediate-energy RI beams, the relative energy E_{rel} of the two fragments A and x , which corresponds to the center-of-mass energy of the $A(x,\gamma)B$ capture reaction, is obtained from their invariant mass extracted from the velocities of A and x and their relative angle. The relative energy resolution δE_{rel} may be

calculated approximately as,

$$\delta E_{\text{rel}} \approx \sqrt{\frac{A_A A_x}{A_A + A_x}} \sqrt{T_0 E_{\text{rel}}} \delta \chi, \quad (1)$$

where A_A and A_x denote the mass numbers of A and x , respectively, and T_0 represents the incident kinetic energy per nucleon. The resolution $\delta \chi$ represents the quadratic sum of the relative-angle resolution $\delta \theta$ (in radian) and the velocity resolution: $\delta \chi^2 = \delta \theta^2 + (\delta v/v)^2$. It is important to note that the relative energy resolution is independent of the energy spread of the incident beam. As an example, δE_{rel} is evaluated to be 200 keV when x is a proton, $T_0 = 100A$ MeV, $E_{\text{rel}} = 1$ MeV, $\delta \theta = 0.6^\circ$ and $\delta v/v = 1\%$. This indicates that the invariant mass method is suitable for experiments with RI beams to achieve a reasonably good energy resolution.

2.2. ^{14}O dissociation and hot CNO cycle

The ^{14}O dissociation discussed above provided a good example for the application of the method to a case of astrophysical interest. When the $^{13}\text{N}(p, \gamma)^{14}\text{O}$ reaction becomes faster than the β^+ decay of ^{13}N , the hot CNO cycle [7] starts instead of the regular CNO cycle. This is expected to occur in the core of super-massive stars, novae or at the surface of neutron stars. The experimental goal is to determine the electromagnetic E1 width Γ_γ of the first 1^- state in ^{14}O , because this resonant state dominates in the stellar $^{13}\text{N}(p, \gamma)^{14}\text{O}$ process. A 87.5 AMeV ^{14}O beam provided by the RIPS fragment separator at RIKEN [8] bombarded a ^{208}Pb target of 350 mg/cm² thickness, and the breakup products ^{13}N and p were detected in coincidence. The radiative width Γ_γ was deduced to be 3.1 ± 0.6 eV [6], which agrees with the width obtained by the direct measurement of the $^{13}\text{N}(p, \gamma)^{14}\text{O}$ reaction performed at Louvain la Neuve [3] almost at the same time as our Coulomb dissociation experiment. Another Coulomb dissociation experiment at 70 AMeV at GANIL [9] also yields a value consistent with the above values within their errors. These agreements demonstrated the power of RI beams, and also indicated the reliability of the Coulomb dissociation method.

2.3. ^8B dissociation and solar neutrinos

The Coulomb dissociation of ^8B simulates the reaction $^7\text{Be}(p, \gamma)^8\text{B}$. This reaction is important for estimating the high-energy neutrino flux relevant to the solar neutrino puzzle, defined as the discrepancy between the measured and predicted neutrino yields from the sun [10]. Direct proton-capture measurements have been performed with a radioactive ^7Be target in many laboratories. In order to study this important reaction by a completely independent method, we have made a series of Coulomb dissociation experiments at RIKEN [11–13].

2.3.1. RIKEN experiments

Unstable ^8B nuclei were produced by the $^{12}\text{C} + ^9\text{Be}$ reaction at 92 AMeV, and were analyzed by the RIPS fragment separator. The ^8B beam energy in the center of the target, 50 mg/cm² ^{208}Pb , was approximately 50 AMeV. The energies of the fragments was determined from their time-of-flight. A $\Delta E - E$ plastic scintillator hodoscope consisting of 10×16 segments was placed 3–5 m from the target. The outgoing particles of the Coulomb dissociation, ^7Be and p , were identified by the $\Delta E - E$ measurement and their scattering

angles were determined from the positions in the segments. These measurements were used to calculate the p - ${}^7\text{Be}$ relative energies. This spectrum was then converted to the ${}^7\text{Be}(p,\gamma){}^8\text{B}$ cross section with the help of a Monte-Carlo simulation which included the detection efficiency and the theoretical Coulomb-dissociation cross sections calculated by the distorted-wave theory.

In the second experiment, the DALI setup, a stack of sixty NaI(Tl) scintillators, was used to measure also the deexcitation γ rays from the first excited state of ${}^7\text{Be}$ at 429 keV populated in the dissociation process. The contribution from this process was measured to be about 5% of the Coulomb dissociation yield.

In Fig. 1 the astrophysical S_{17} -factors obtained in the first and second experiments are shown together with the results from direct (p,γ) measurements. The S -factor is related to the capture cross section σ by

$$S = \sigma E \exp[2\pi\eta] \quad (2)$$

Figure 1. Astrophysical S_{17} -factors for the ${}^7\text{Be}(p,\gamma){}^8\text{B}$ reaction extracted from the first (large open circles) and second (large solid circles) experiments at RIKEN. Existing direct (p,γ) data are also shown. The solid and dashed curves represent the fits to the data from the second Coulomb dissociation experiment with the theoretical energy dependence of Barker and Spear [14] and of Descouvemont and Baye [15], respectively.

with the Sommerfeld parameter $\eta = e^2 Z_1 Z_2 / \hbar v$ and center-of-mass energy E . Our Coulomb dissociation data are consistent within errors with the results by Filippone *et al.* [16] and Vaughn *et al.* [17]. The S factor extrapolated to zero energy, $S_{17}(0)$, for the second experiment which had better accuracy is 18.9 ± 1.8 eV-b [13]. This is within the range of the most recent recommendation 19^{+4}_{-2} eV-b [18], which was extracted from selected direct capture data.

2.3.2. GSI experiment

Another experiment at a higher incident energy of 254 AMeV has been performed at GSI [19]. In general, higher order processes are less important at higher incident energy, and this experiment might provide a good test for the reaction mechanism in comparison with the lower energy results of the RIKEN experiment. A ^8B beam was produced by fragmentation of a 350 AMeV ^{12}C beam from the SIS accelerator bombarding an 8.01 g/cm² beryllium target. The beam was isotopically separated in the fragment separator (FRS) [20] and transported to the target position of the spectrometer KaoS [21]. The outgoing proton and ^8B nucleus from the Coulomb dissociation in the field of a ^{208}Pb target were momentum-analyzed and detected in coincidence at the KaoS focal plane. The scattering angles of these particles were determined by silicon microstrip detectors set between the target and the spectrometer. The result $S_{17}(0) = 20.6 \pm 1.2 \pm 1.0$ eV-b agrees with the RIKEN data and hence with the direct capture data with lower S -factors.

2.3.3. E2 component

These results suggest that the S_{17} factor is not far from the one recommended and used in solar model calculations [22]. However, for more accurate determination of the S_{17} factor by Coulomb dissociation, investigation on the reaction mechanism is required. For example, the role of the E2-mixture in the dominant E1 component and effects of higher-order processes have been discussed.

It was pointed out that possible E2 contribution can affect the Coulomb dissociation results [23]. The $^7\text{Be}(p, \gamma)^8\text{B}$ reaction is dominated by E1 γ -emission through continuum states. The E2 amplitudes are very small, but they are enhanced in the Coulomb dissociation process because of its much higher sensitivity compared to E1 transitions as demonstrated in Fig. 2. On the other hand, the M1 transition is suppressed in the Coulomb dissociation, while it might have a certain contribution in the direct (p, γ) process.

The second RIKEN experiment was aimed at measuring the E2 component from the precise angular distribution of θ_8 , the scattering angle of the p - ^7Be center-of-mass. In the vicinity of the grazing angle, the E1 angular distribution decreases, whereas the E2 cross section stays almost constant. Therefore, the E2 contribution may be observed at large angles even if it is small. The results are shown in Fig. 3. Surprisingly the mixture of the E2 component is negligibly small [12]. It should be pointed out that the analysis shown in Fig. 3 include the $\ell=2$ nuclear component, which might have similar or even larger magnitude compared with the corresponding Coulomb or E2 component as will be discussed later and shown in Fig. 4.

For the same purpose, the extraction of the E2 component, the parallel-momentum distribution of the ^7Be fragment from the Coulomb dissociation of ^8B has been measured at MSU [24]. They observed asymmetric peak shapes that are explained as an interference

Figure 2. Number of virtual photons plotted as a function of the incident energy of the ${}^8\text{B}+{}^{208}\text{Pb}$ reaction. The $p-{}^7\text{Be}$ relative energy in the final state is assumed to be 500 keV. The solid, dashed and dash-dotted curves represent E1, E2 (scaled by 1/300) and M1 transitions, respectively.

Figure 3. Measured angular distribution for the Coulomb dissociation of ${}^8\text{B}$ for two relative energy bins. The best fits result in pure E1 transitions (solid curves). Dashed and dotted curves correspond to two different models which are normalized to the data by fixing the ratios between the $\ell=1$ and $\ell=2$ components to the theoretical predictions. The $\ell=1$ nuclear amplitudes are not included, because they are expected to be negligibly small.

between E1 and E2 amplitudes. The extracted E2 component is of the same order of magnitude as those predicted by nuclear structure models for ${}^8\text{B}$. This conclusion is in contradiction to the angular distribution measurement, requiring further studies. It should be noted that the $\ell=2$ nuclear component is not included in the analysis of the parallel-momentum distribution [24].

2.4. Hot-pp mode reactions

Encouraged by the results described above, we are applying the method to a few more systems. Recently, we performed experiments of the dissociation of ${}^9\text{C}$, ${}^{12}\text{N}$, and ${}^{13}\text{O}$, which are intended to determine reaction rates relevant to the hot-pp mode of nuclear burning in hydrogen-rich massive objects [25]. Except for the ${}^{12}\text{N}$ dissociation experiment performed at GSI by an Orsay group [26], no experimental information is available for the corresponding (p,γ) cross sections. In the network calculation for the hot pp mode by Wiescher *et al.* [25], these cross sections were evaluated by simple nuclear-structure calculations. Our studies were aimed at improving this situation by providing experimental data through Coulomb dissociation experiments.

The experiments have been performed by essentially the same procedure as in the ${}^8\text{B}$ dissociation experiments. Our preliminary analysis already suggest several interesting

features. Due to the better energy resolution, the E1 transition in ^{12}N from the 1^+ ground state to the excited 2^- state at 1.191 MeV could be rather well separated from the M1/E2 transition to the first excited state at 0.960 MeV with $j^\pi=2^+$. Since they are not resolved in the spectrum obtained in the earlier study [26], more accurate extraction of the E1 radiative width might be possible. The p - ^{12}N relative-energy spectrum obtained in the ^{13}O dissociation experiment exhibits low energy E1 strength below the known state at 2.75 MeV excitation energy. Not only for astrophysical interest, the observed low-energy E1 strength is important in connection with studies of the structure of light drip-line nuclei. For example, this E1 strength is qualitatively in agreement with the prediction of a large-scale shell model [27], but is not observed in the mirror nucleus ^{13}B by the $^{11}\text{B}(t,p)$ reaction [28] or the neutron knockout reaction [29].

2.5. Future tests of the Coulomb dissociation method

In the experiment of the ^{14}O dissociation, we also have studied ^{13}N [6]. The data could be used to extract the radiative width of the $1/2^+$ resonant state in ^{13}N . This is a good test to check the reliability of the Coulomb dissociation method, because the width has been measured by several $^{12}\text{C}(p,\gamma)^{13}\text{N}$ experiments directly. Our result $\Gamma_\gamma=0.59\pm0.18$ eV-b [6] agrees with the latest compilation 0.50 ± 0.04 eV-b [30]. However, due to the insufficient resolutions for the relative energy and reaction Q -value, the Coulomb dissociation result had a large error of 30%, and hence the reliability of the method could be tested only to this accuracy. In order to improve the accuracy, we performed a new experiment of Coulomb dissociation of ^{13}N and ^{14}O with a new setup with better resolutions. Preliminary analyses result in resonance peaks in the relative energy spectra with a factor of two better resolution compared with those in the previous measurements [6].

3. COULOMB EXCITATION

3.1. Coulomb excitation at intermediate energies

If the nucleus of interest is excited to the region below the particle- decay threshold, it decays by γ -ray emission. It is sometimes difficult in inelastic scattering experiments with reversed kinematics to resolve excited states by measuring the particle energy due to the large energy-spread of RI beams. This difficulty may be solved by measuring the γ ray from the excited state in coincidence with the scattered nucleus. Especially for the Coulomb excitation, the angular distribution of the scattering is reliably predicted, and the γ ray yield can directly be related to the electromagnetic transition probability with a small ambiguity in the case where an intermediate-energy RI-beam is used.

The usefulness of the method has been demonstrated for the first time for the very neutron rich nucleus ^{32}Mg [2], which is frequently quoted in the present symposium. Together with the extensive studies by the MSU group [31], intermediate-energy Coulomb excitation becomes a standard method of spectroscopy for unstable nuclei.

Because the incident energy is much higher than the Coulomb barrier, the potential influence from nuclear excitation should be considered. Figure 4 shows the relative importance of the Coulomb and nuclear excitations for $\ell=1$ (E1) and $\ell=2$ (E2) transitions [32], where ℓ denotes the angular momentum transfer. The calculation is for the inelastic scattering between ^{208}Pb and a nuclei with atomic number Z at 70A MeV incident energy, which excites a state at 5 MeV in the nucleus “Z”. The cross sections are calculated by

Figure 4. Atomic number dependence of the Coulomb and nuclear excitation cross sections for the process, $Z + {}^{208}\text{Pb} \rightarrow Z^* + {}^{208}\text{Pb}$, where a nucleus with atomic number Z is excited to a state at 5 MeV. The incident energy is to 70 A MeV. The left panel corresponds to $\ell=1$ (E1) and the right panel to $\ell=2$ (E2) transitions.

assuming a constant collective deformation parameter. The Coulomb cross sections are obtained by the semi-classical virtual photon theory developed by Baur, Bertulani and Rebel [4], whereas the nuclear ones are calculated by the distorted-wave theory where the transition from factors are obtained by the “standard” procedure used in light-ion induced inelastic scattering, based on the derivative of the optical potential. For the $\ell=1$ nuclear excitation, the results are checked by calculations with microscopic transition form factors for ${}^8\text{B}$ [33] and ${}^{14}\text{O}$ [34]. As indicated in the figure, Coulomb excitation dominates for Z above ≈ 10 for $\ell=2$. On the other hand, E1 Coulomb excitation is always much larger than $\ell=1$ nuclear excitation.

3.2. Coulomb excitation of ${}^{15}\text{O}$

We applied the E1 Coulomb excitation to an astrophysical reaction, aiming at extracting the radiative width of a subthreshold state. The low-energy behavior of the hot-CNO reaction ${}^{14}\text{N}(p,\gamma){}^{15}\text{O}$ is still ambiguous due to the subthreshold state in ${}^{15}\text{O}$ at 6.793 MeV excitation energy with $j^\pi=3/2^+$. Depending on the strength, its high-energy tail may affect the (p,γ) cross section at low energies [35].

Radioactive ${}^{15}\text{O}$ beams were provided by the RIPS fragment separator, and bombarded a 1480 mg/cm^2 thick lead target with 85 A MeV energy. Outgoing ${}^{15}\text{O}$ nuclei were identified by the plastic scintillator hodoscope that is essentially the same as the one used in the ${}^8\text{B}$ dissociation experiments. Deexcitation γ rays were measured in coincidence by the DALI setup mentioned in sect. 2.3.1. An example of the Doppler-corrected energy spectrum of γ rays is shown in Fig. 5. The spectrum contains some yield from excited states of the target nucleus ${}^{208}\text{Pb}$. However, almost no yield from ${}^{208}\text{Pb}$ is expected in the region where the peak due to the E1 excitation of interest is expected. The two dashed

Figure 5. Doppler-corrected spectrum for γ rays measured in coincidence with scattered ^{15}O from 85 AMeV $^{15}\text{O}+\text{Pb}$ Coulomb excitation. The two dashed curves represent the results of calculations assuming a width Γ_γ of 6.3 eV and 0.87 eV for the $3/2^+$ state at an excitation energy of 6.793 MeV in ^{15}O .

curves at around 6.5 MeV are the simulated peaks by assuming two different predictions for the electromagnetic width, $\Gamma_\gamma=6.3$ eV [35] and $\Gamma_\gamma=0.87$ eV [36]. As can be seen in the figure, the larger width of 6.3 eV is not consistent with the data, whereas the smaller width of 0.87 eV is compatible with the data, suggesting a width about 1 eV or smaller. This points to negligible influence of the $3/2^+$ state to the low-energy behavior of the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction.

4. SUMMARY

Some results from Coulomb dissociation and Coulomb excitation experiments were presented as examples of applications of intermediate-energy RI beams to nuclear astrophysics studies. The advantages of these experimental studies are the large cross section and the possibility to use thick targets. This enables one to investigate astrophysical reactions involving unstable nuclei with reasonable statistics. By measuring the invariant mass or the energy of deexcitation γ rays, the final state to be studied can be reasonably well resolved, almost independent of the large energy and angular spreads of RI beams.

In evaluating reaction rates for nuclear burning, properties of resonant and continuum states just above and sometimes below the particle threshold are important. Any spectroscopic methods that are capable of studying these states should be applicable to astrophysics problems. For example, determination of the spin and parity of a resonant state can be achieved by particle transfer reactions in reversed kinematics. We are trying to measure the vector analyzing power of the $(^3\text{He},\alpha)$ reaction using a polarized ^3He

target developed at RIKEN [37]. The relatively simple angular dependence of the analyzing power might enable one to determine the j value of the final state even with a poor angular resolution.

Finally, it should be pointed out that further theoretical investigations of the reaction mechanisms are necessary in order to accurately extract spectroscopic quantities of the excited states of astrophysical interest.

The works presented in this report have been performed in collaboration with Y. Ando, H. Fujiwara, T. Gomi, Y. Higurashi, I. Hisanaga, K. Ieki, T. Kijima, T. Kikuchi, H. Kobayashi, T. Minemura, S. Moriya, H. Murakami, S. Ozawa, J. Ruan (Gen), M. Scrata, S. Shirato, T. Takei, S. Takeuchi, T. Uchibori, K. Yamada, Y. Yanagisawa (*Rikkyo Univ.*), H. Akiyoshi, A. Goto, T. Ichihara, N. Inabe, M. Ishihara, T. Kubo, M. Kurokawa, A. Ozawa, Y. Watanabe, K. Yoshida (*RIKEN*), N. Aoi, N. Fukuda, N. Imai, H. Iwasaki, M. Notani, H. Sakurai (*Univ. Tokyo*), S. Kubono, Z. Liu, S. Shimoura, T. Teranishi (*CNS, Univ. Tokyo*), N. Iwasa (*Tohoku Univ.*), S. Kox, F. Merchez, C. Perrin, D. Rebreyend (*INS Gernoble*), Z. Zhao (*Yale Univ.*), R.H. France III, M. Gai (*Univ. Connecticut*), K.I. Hahn (*Ewha Womens Univ.*), K. Furutaka, T. Nakamura (*Tokyo Inst. Tech.*), Th. Delbar, P. Lipnik, C. Michotte (*Louvain la Neuve*), Y. Futami, Y. Iwata, M. Hirai (*Inst. Radiol. Sci.*), F. Boué, T. Baumann, H. Geissel, Hellström, P. Koczon, E. Schwab, W. Schwab, P. Senger, K. Sümmerer, G. Surówka, A. Surowiec, (*GSI*), B. Blank, S. Czajkowski, M.S. Pravikoff (*Bordeaux*), A. Förster, F. Laue, H. Oeschler, C. Sturm, F. Uhlig, A. Wagner (*TU Darmstadt*), E. Grosse (*Dresden*), B. Kohlmeyer, J. Speer (*Marburg*), R. Kulesa, C. Marchand, W. Walus (*Krakow*), C.A. Bertulani (*Rio de Janeiro*), and Z. Fülöp (*ATOMKI*).

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